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Part 3

03

SATELLITE MAPPING — REGIONAL GEOLOGY, GEOMORPHOLOGY, STRUCTURE, DRAINAGE AND HYDROLOGY OF

BAHR EL JEBEL AREA

SOUTHERN SUDAN

(JONGLEI CANAL PROJECT AREA)



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SATELLITE MAPPING— BAHR EL JEBEL AREA, SOUTHERN SUDAN

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SATELLITE MAPPING-

REGIONAL GEOLOGY, GEOMORPHOLOGY, STRUCTURE, DRAINAGE AND HYDROLOGY OF BAHR EL GEBEL AREA

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abstract

The River Nile originates in Central Africa where it starts to flow under the name of Victoria Nile. It assumes the names Albert Nile and Bahr El Jebel at the eastern end of Lake Albert and at Nimule on the southern border of Sudan respectively. At El Sudd Region in Southern Sudan, Bahr El Jebel enters an almost flat alluvial plain where the river course becomes highly ramified and infested by swamps largely covered with vegetation, there the main channel of Bahr El Jebel is sufficient to carry its water discharge when the water is low, however, Bahr El Jebel overflows its banks as the water rises leading the great losses of water by seepage, evaporation and evapotranspiration (Hurst, et al., 1932-present). During the months of May, June, July, August, September, October, November and December the average monthly discharge of Bahr El Jebel at Mongalla normally exceeds two thousand million m^3, while in the months of January, February, March and April the average monthly discharge is less than two thousand million m^3.

One of the most accepted means of overcoming the water losses at Bahr El Jebel in Southern Sudan, estimated at 12,250 million m^3 annually, is its canalization through a canal some 280 km long connecting Jonglei on Bahr El Jebel with Malakal on the White Nile. This scheme is called the Jonglei Canal Project.

The regional mapping and study of the huge Jonglei Canal Project area represent an ideal case for the application of Landsat imagery

interpretation especially in view of the inaccessibility of most of its coverage, notably in the long rainy season. The implementation of this work has been carried out through Landsat imagery interpretation in both the dry season and the wet season together with low reconnaissance flying, ground field work along passable roads and tracks, and extensive laboratory analyses. In the present part of the work maps are presented for the geological and environmental units, structural lineations, lineation density, surface drainage and surface water bodies and groundwater. Landsat imagery interpretation has thus provided, within a short period of time, including the preparatory period, a regional picture for such a unique area of investigation covering 165,000 *km*^{2}.

Chapter I

geomorphology and drainage

On the basis of Landsat-1 satellite imagery interpretation and field studies, two drainage maps for Jonglei Canal Project area have been constructed — the first during the dry season (Fig. 2a) and the second during the wet season (Fig. 2b). Moreover, the general surface water conditions in the studied area during the same seasons are illustrated on a separate map (Fig. 6). On these maps, it has been possible to distinguish between perennial and seasonal drainage lines, the direction of general water flow, the drainage pattern and the density variations in drainage lines.

The area studied is traversed by four main river courses, namely Bahr El Jebel, Bahr Ez Zeraf, White Nile and River Sobat. The first two and the last one drain into the White Nile which eventually flows northwards (Fig. 1). The main drainage lines drain into the main rivers, the former attaining various directions of flow which are mainly northwest, northeast, north and south (Figs. 2a, 2b).

The drainage pattern and the geomorphology of the studied area vary according to its geology and structure. Accordingly, the area has been divided into four geomorphologic units each possessing certain drainage patterns, these are the basement upland unit, the lateritic-covered unit, the seasonal flood plain unit and the perennial flood plain unit.

Basement Upland Unit

This unit is characterized by high relief, gradational contact with the lateritic covered country and the absence of flooding. It covers nearly all the southern part of the studied area (Fig. 6). The drainage pattern is ranging from dense dendritic to trellis types and the drainage lines are narrow and deep. The pattern is controlled by relief, joints, fractures including faults, folding, gniessosity and other lineaments. Accordingly, the degree of uniformity of the drainage lines and their angle of junction differ from place to place. The direction of flow is oriented to the east and to the west around Bahr El Jebel and to the north in other parts of the unit (Fig. 2a).

Lateritic-covered Unit

This unit occupies a rather wide zone extending generally in a NW-SE direction and it lies to the south of Yirol-Mongalla line (Fig. 6). The unit is characterized by the presence of drainage lines of moderate density which belong to the dendritic type and they exhibit a high degree of branching on the slope of the highlands. Moreover, the channels of the drainage lines are wide and seasonal in the low parts.

The area of the lateritic-covered unit is divided into two subunits according to relief, namely the high undulating land to the south with high density drainage lines and the low lateritic-covered plain which is partly covered by clay especially near the channels. Yirol, Anyi, Nubo and other small lakes, extending in a nearly straight line in the low plain, are mainly structurally controlled. It is important to mention here that most of the main drainage channels which cross this unit end with elongated lakes before their connection with Bahr El Jebel course especially from its western side.

Seasonal Flood Plain

This clay plain extends mainly to the north and to the east of the main river courses, and it is formed of slightly undulated land. The higher parts are occupied by low sand ridges (Qoz) which are about 1 m high. The plain is mainly seasonally flooded by water derived from the surrounding high country, especially during the rainy season when sheet flooding occurs in the lower parts. The drainage channels are darker in Landsat images in the rainy season relative to the dry season. These drainage lines are characterized by their dendritic pattern of long tributaries, with the main streams draining mainly to the northwest. The parts occupied by the sand ridges are less subjected to drainage, and they are either not flooded or flooded under shallow water depending on lithology and relief. The ridges themselves appear as light grey zones on Landsat images.

Perennial Flood Plain

This plain may be also termed El Sudd plain, and it covers the area in the immediate environs of Bahr El Jebel and Bahr Ez Zaraf in the northern part of the mapped area, however, it extends south-

wards to the neighbourhood of Juba (Figs. 2a, 2b). On Landsat images this plain appears in dark tone in all seasons except where savanna and other vegetation become dense. The degree of darkness of the tone depends upon the amount of water and moisture present. The plain is characterized by a complicated drainage pattern. To the west of Lake No (Figs. 2a and 2b) the water course is formed of changing almost shallow dense braided channels. The latter are responsible for the waterlogging of the surrounding environment especially during the flood season. El Sudd plain, in general, is characterized by complex meandering network of separate channels connected with Bahr El Jebel and Bahr Ez Zaraf. These channels are mainly shallow, wide and they form in some parts swamps and lakes of perennial nature.

The plain in question represents the lowest part in the studied area in which vegetation belongs mainly to the savanna. The vegetation is of low density in the central zone, but becomes more dense on the two banks of Bahr El Jebel and extends in a long strip parallel to the main water course but slightly scattered around Bahr Ez Zaraf. Vegetation appears in the form of zones exhibiting a light tone in band 7 of Landsat images. It is worth mentioning that the lakes, lagoons and swamps which surround Bahr El Jebel are present in the lowest levels of El Sudd plain.

In the area to the south of Bahr El Jebel and Bahr Ez Zaraf connection, the lakes and lagoons become more abundant and they are connected by complex meandering channels in which the main river course is hardly observed. Swamps and vegetation in this part become less dense or scarce especially around the lakes. Between Mallik and Juba, the lakes become less abundant to scarce, but the meandering channels become more common (Fig. 2a).

To the southwest of El Sudd plain and to the west of Yirol, there exists a long and deep basin filled with clay which is generally a flat land dissected by numerous channels, with the latter causing seasonal flooding in the basin. Moreover, the southern parts of the basin are highly vegetated in comparison to its other parts. In the satellite images the former parts appear during both the dry and the rainy seasons in lighter tone in comparison to the other parts of the basin which become darker in the rainy season. Moreover, some scattered lakes are present in these southern parts.

Chapter 2

structure

The structural lineaments in Jonglei Canal Project area have been delineated and interpreted as fractures including faults and folds (Fig. 3) on Landsat images. The lineaments are 878 in number and they have been computed and contoured on a lineament density map (Fig. 4a). Moreover, they have been statistically analyzed and rose diagrams for length and number distribution are constructed (Figs. 4b, 4c, 4d). The geomorphologic and physiographic features in the studied area are evidently greatly controlled by its structural and lithological units.

Fractures

Landsat imagery interpretation of Jonglei Canal Project area delineated six sets of fractures (including faults) which follow the NNW-SSE and NW-SE, ENE-WSW and NE-SW, and NNE-SSW and ENE-WSW trends. The first two are the most predominating sets, while the third and fourth are of moderate distribution and the fifth and sixth sets are of minor importance. Whiteman (1971) mentioned that most of the structural trends in the Southern Sudan vary from 160° to 180°, i.e., from N20°W-S20°E to N-S, however, the results of the present work show the superiority of the presently applied space-borne technology in the Jonglei Canal Project area.

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The NNW-SSE set includes the fractures striking N20°-40°—S20°-40°E with a mean strike of N35°W-S35°E direction. Some faults belonging to this set show dextral strike-slip movements.

The NW-SE set incorporates the fractures striking N40°-50°W—S40°-50°E with a mean strike of N45°W-S45°E direction. The two sets under consideration are widely distributed in the investigated area, and together with the other four sets they give the major sedimentary basin, extending from Nuba Mountains in the north to the basement outcrops in the proximity of Juba, its configuration and eventually its present environment and its dominating swampy nature. The NW-SE fracture set is roughly parallel to the axial trace of a major fold trend including Duk Faiwil and Juba folds (Fig. 3). It appears that some NW-SE faults located to the northwest of Torit (Fig. 3) possess a dextral strike-slip separation while others have a sinistral strike-slip separation. Furthermore, a major shear zone named Torit shear zone which extends intermittently for more than 350 km belongs to the treated NW-SE sets. In addition, a major fault belonging to Nimule shear zone extending intermittently for more than 300 km is dislocated by ENE-WSW trending faults to the northwest of Nimule (Fig. 3). This proves that some fractures belonging to the NW-SE set are apparently older in age than the associated ENE-WSW fractures. The ENE-WSW fracture set strikes N50°-80°E—S50°-80°W, with a mean strike of N65°E-S65°W. Some faults belonging to this set apparently show dextral strike-slip separation while others exhibit sinistral strike-slip separation as noticed to the northwest of Nimule (Fig. 3).

The NE-SW fracture set exhibits N40°-50°E—S40°-50°W strike with a mean of N45°E-S45°W. The lineaments of NE-SW and the ENE-WSW sets are roughly parallel to the axial traces of some double plunging folds especially well exhibited in the southern basement exposures (Fig. 3). Moreover, the mentioned two fracture sets are more common in the southern basement exposures relative to the northern sedimentary cover (Figs. 4b, 4c).

The NNE-SSW fracture set shows N20°-40°E—S20°-40°W strike with a mean of N25°E-S25°W. This set is of minor distribution and some of its fractures are roughly parallel to the axial traces of some mesoscopic folds appearing especially in the basement (Fig. 3).

It is important to mention that a WNW-ESE fault is delineated from satellite images in the northern part of the studied area, which follows the course of the White Nile (Fig. 3). The delineated fault is about 125 km in length and it shows a dextral strike-slip separation. The fault in question is apparently responsible for the great bending of the White Nile to the westsouthwest of Malakal. The horizontal separation along the discussed fault is probably in

the order of magnitude of tens of km, however, due to the absence of clear geological features on both sides of the fault it has not been possible to estimate correctly the horizontal separation.

The distribution of the previously mentioned linear elements in the studied area is treated by the construction of a lineament density map (Fig. 4a). This map reveals remarkable variations in lineament density between the sedimentary cover and the basement. The former is characterized by the presence of relatively low densities of lineaments which range from 0.025 to 0.200 and accordingly the contour lines are widely spaced. On the other hand, the lineament distribution in the basement is of relatively high density since it ranges from 0.025 to 0.300, while the contour lines expressing the density are closely spaced. This result is due to several factors including the greater brittleness of the basement rocks, the better basement exposures and the greater number of tectonic events which influenced the basement.

Folds

The curved lineaments delineated by Landsat imagery interpretation are represented mainly by macroscopic folds and by circular structures. Frequency distribution of ninety axes of the delineated fold traces shows the presence of four sets with axial traces trending N-S, NW-SE, NE-SW and ENE-WSW (Fig. 4e).

The N-S axial traces of the folds of the first set range from N 10°W-S10°E to N10°E-S10°W, and the set is represented by large to moderate scale folds. The most interesting fold is located some 60 km to the east of Bor-Malakal line with an axial trace extending for more than 300 km towards the outside of the investigated area. A considerable part of western limb of the fold in question is located in the eastern part of the mapped area and it is correlated with some drainage lines, fractures and bedding attitudes in the land between Bor and Malakal (Fig. 3). Moreover, many folds belonging to the considered set are scattered in the basement and they are of moderate to small magnitude and with relatively steeply inclined limbs. These folds are doubly plunging and rather tight in character.

The NW-SE axial traces of the folds of the second set strike in N30°-50°W—S30°-50°E directions. The folds belonging to this set influence considerably the distribution of the sedimentary cover and the basement rocks, as well as the shape of some of the main river courses in the mapped area. The axial trace of Duk Faiwil fold, which is the main one, has been mentioned before (Whiteman, 1971), but some parallel axial traces of folds are recorded for the first time in the present work. In Juba area, a fold of regional

dimension appears to be partly responsible for the great curvature of Bahr El Jebel, and the associated main drainage and fracture lines.

The NE-SW axial traces of the third set of folds trend N20°E-S20°W and N60°E-S60°W. Actually, it may represent NNE-SSW and NE-SW trends. The discussed folds appear to be rather scarce in the sedimentary cover, while they are well developed in the basement (Fig. 3). Most of the folds belonging to this set are closed and doubly plunging in character.

The ENE-WSW axial traces of the fourth set of folds possess N70°-80°E—S70°-80°W trends. This set is relatively less abundant than the formerly discussed three sets and it is mainly developed in the basement.

Tectonic Events

Guided by the distribution of lithologic units and the statistical counting of the linear trends of axial traces bisecting the curved lineaments, it could be speculated that the tectonic events to which Jonglei Canal Project area have been subjected are the Laramide and the Alpine diastrophisms.

The Laramide deformation affected the basement rocks and the Cretaceous Yirol Formation. For this reason a Late Cretaceous age is assigned to the peak for this deformation. The relatively plastic deformation is expressed as folding of regional scale with N-S to NW-SE axial traces. In other words, the folding in the area considered is of the branching type. The southern part of Bahr El Jebel is mostly coincident with an axis of a major syncline trending nearly N-S and plunging gently to N. This syncline starts near Junglei and diverges into two major synclines ; one N-S while the other is approximately NW-SE. These two synclines are separated by an uplifted zone which may represent an anticline along which the flood and swampy plain is superimposed.

The Alpine deformation of rupture character is expressed by major slight open folding with an axial trace striking nearly ENE-WSW and to a great extent by major fractures trending NW-SE, N-S and E-W. The first two fracture sets are most probably representing conjugate shear planes while the third one is tensional in character. Weak folding occurred during the discussed deformation which created certain pattern of structural features when superimposed on the older Laramide deformation. The younger deformation is of Alpine age and it extends into the late Tertiary. The River Nile owes its origin in particular to this deformation. The superimposition of the previously mentioned two generations of folding created major basins and domes of semicircular or crescent shapes.

Impact of Lineaments on Jonglei Canal Project

It has been proposed that Jonglei Canal may be dug between Jonglei and Malakal. An alternative idea is to dig the canal between Bor and Malakal. The lineament density map (Fig. 4a) shows that the land crossed by the projected Jonglei Canal is structurally calm. These major fracture lines are apparently covered with thick sedimentary units. Moreover, the folding structures imposed on the northern sedimentary cover are of rather open type where no major sharp crenulations are recorded. Accordingly, the proposed Jonglei Canal site is generally suitable from a structural point of view. However, the zone around this line should be subjected to a detailed structural study.

The drainage maps in the dry and the wet seasons (Figs. 2a, 2b) show in a clear manner the drainage lines which will encounter the proposed canal and their nature. Accordingly, these maps could be utilized in planning the Canal course.

Chapter 3

geological and environmental units

In the Jonglei Canal Project area, the basement rocks outcrop at the southern part while the northern part is covered by sedimentary rocks and sediments mostly of Cretaceous and Quaternary ages. The basement rocks are partly covered by lateritic soils. The younger units such as Yirol Formation and Umm Rawaba Formation are mostly buried under thick cover of surficial deposits, except at Yirol locality, where the Yirol Formation is exposed.

The basement and the sedimentary cover, *sinsu strictu,* are invaded by some dyke-form, ring-shaped, vein-like bodies and plugs composed of quartzite, porphyry, syenites and some granitic rocks distributed in the area of study. Most of these bodies are of Late Cretaceous age, although some of them cover a longer time span.

Precambrian Igneous-Metamorphic Rocks

These rocks are mainly cropping out in the southern part of the area under investigation. They are dominantly gneisses carrying biotite or hornblende or both, although some charnokitic and related rocks are more conspicuous to the south. The injection gneisses and the granitic rocks make remarkable masses associated with the other rocks in the area of investigation.

Charnockitic and Related Rocks : (Andrew, 1948) recognized charnockitic rocks similar to those present in Northern Uganda. These

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rocks were isolated on the geological map of the Sudan, southern sheet, 1 : 2000,000, (Vail, 1974), as related to the granulite rocks. These rocks are considered by Whiteman (1971) as equivalent to the older orthogneiss of Sudan (Delany in Whiteman, 1971) and to para- and orthogneisses of Northern Red Sea Hills (Kabesh in Whiteman, 1971).

On the new map (Fig. 5) interpreted from satellite images, these units are delineated according to similarity of the charnockitic rocks to those located on the previous maps. These rocks are characterized by the presence of notable contortions and fractures. They appear on Landsat images in medium grey toned units with coarse textured surfaces and they occupy the southern part of the country as a continuation to the charnockitic rocks of Northern Uganda. Some patches with similar features could be delineated to the east and west of Juba. The charnockitic rocks have been subjected to a grade of metamorphism corresponding to the most intense amphibolite facies.

Gneisses : These rocks are exposed in the area of study where they form low or moderately hilly country. The gneisses show variable features on Landsat images but generally they have distinct properties. Their grey tones are ranging from medium to light, and their textures are mainly fine and medium. Four units of gneisses have been delineated on the geological map, which include hornblende, biotite-rich, biotite and injected gneisses.

Hornblende gneiss is well represented at Juba, and it is intercalated at some places with banded mica gneiss. In general, the gneiss forms folia or sheets dipping SE/35°. The hornblende gneiss is also exposed to the west of Nimule and in the western part of the investigated area at latitude 5° N where well foliated acid gneiss bands and coarse pegmatites with NNW/20° dip are associated.

Biotite-rich and biotite gneisses show frequent outcrops to the east or the west of Bahr El Jebel. These outcrops are forming scattered moderately to highly elevated hills partly covered by forests. The gneisses are fine to medium grained, non porphyritic and whitish to dark grey in colour. The foliation present in the gneisses to the east of Gebel Lungy is trending NE-SW, and dipping to NW. Recumbant, isoclinal and open folds are observed in the gneisses in question. The differences between the biotite and the biotite-rich gneisses are better expressed in texture rather than in tone as the foliation in the biotite-rich gneiss is more clear than in the biotite gneiss.

Injected gneiss shows augen texture and is highly sheared and fairly homogeneous except for few hills where the gneiss possesses porphyritic texture and darker tone. Numerous outcrops of well foliated feldspathic gneiss with quartz and pegmatite veins are seen to dip to SW by about 60°. At other locations the strike shifts to

become N-S. The darker variety of the gneiss is found as elongated ridges with distinctive dense fracturing. The rock is coarse to medium grained, hard and greyish to whitish in colour. It is essentially composed of feldspars, biotite and/or hornblende and quartz. It seems to be affected by nearby granitic intrusions which seem to be always present at the gneiss contacts. The gneiss is also cut by basic dykes which are mostly trending NW-SE.

Granodiorite, pink granites and other granitoid rocks include the relatively older granodiorites and the relatively younger granitic rocks. The granodiorites are mostly characterized by gneissose texture and abundant ferromagnesian minerals while the granitic rocks show the presence of riebeckite mineral. These rocks can be differentiated on Landsat images by their variable tone, texture and real extension. The pink granites appear lighter in tone and coarser in texture in comparison to the granodiorite exposures. The smaller outcrops, which are mostly granitoids, form ring-like features or plugs possessing mostly fine texture and grey tone. They are found in locations covered either by lateritic or other soils to the north.

Phanerozoic Igneous Bodies

These rocks include quartzites on fault zones, porphyry and other dykes, syenites, granites, and small igneous bodies.

Quartzites : These rocks occur in bands trending NW-SE and they form low hills of rounded form. They show drag folding and common crushing. The quartzites form elongated ridges along major shear zones. The most distinct ridge is that called Maadi shear zone extending from Nimule northwest for more than 100 km. This shear zone is most probably the extension of Assua trend of North Uganda.

Porphyry and other dykes are mostly of lamprophyric and basaltic composition. They are mostly controlled by faults and fractures and they invade the Precambrian rocks and the Maadi quartzite itself. These are clustered also in a clear manner at the intersection of long. 30°E and lat. 5°N. Smaller dykes are present to the east and to the west of Bahr El Jebel, however, they are too short in length to be recorded on the map.

Syenites and other granitic rocks form ring structures and plugs. They include syenites and nepheline syenites which are well jointed but still highly resistant to weathering. These are also bodies of granitic composition such as Gebel Ez Zeraf. The syenites appear in light grey tone and fine texture on the Landsat images, while the granitic bodies appear lighter in tone and smoother in texture.

Yirol Formation

This includes clastic sediments exposed near Yirol. They are made up of sandstones and grits interbedded by mudstones and clays. They possess undulating surfaces and they are mostly overlain by thin deposits of clays in Yirol locality while in other localities they are expected to be covered by thick surficial deposits.

Quaternary Deposits

These deposits include either residual deposits or transported sediments. The residual deposits are mainly represented by the lateritic soils while the transported sediments cover the plains and fill the valleys.

Lateritic Soils : These mainly outcrop to the north of the basement exposures. On Landsat images, they show characteristic features and they vary slightly in tone and texture, but generally they possess medium grey tone and coarse texture. The lateritic deposits are variable in thickness from less than 1 m to some 30 m where they overlie the basement. Generally the lateritic soils include an uppermost bed of red ironstone. The variation of surface textures of the lateritic soil from south to north is mostly due to the difference in conditions of deposition. On the top of the basement highlands, the lateritic soils form a distinct horizon with low density drainage pattern. Due north the basement highlands start to slope down and the drainage density increases and the lateritic soils there seem to be transported for short distances along channels and on low relief hills.

Terraces and Valley Fill Deposits : These include the deposits filling the main streams of Bahr El Jebel, the White Nile and their tributaries, and the deposits of the terraces and plains bounding Bahr El Jebel and the White Nile. The terraces are mainly covered by sands, grits, clays and silts according to the conditions controlling their formation. They are perennially covered by water whether shallow or deep. The plains to the east of Bahr El Jebel and to the north of the White Nile are covered by silty and sandy soils. The different soil types are delineated on the satellite images considering their vegetation cover. The deposits covering the main channels of Bahr El Jebel and the White Nile and their tributaries are mainly composed of clay and silt in addition to gravel which is encountered at the medial parts.

The Quaternary units encountered in the path of the proposed Jonglei Canal are shown on the map of the geological and environmental units (Fig. 5). The Quaternary units in particular have strong environmental implications on the projected canal site and on the area as a whole regarding its reclamation and development.

Chapter 4

Hydrology

Scope

The scope of this study is to evaluate the groundwater resources of the Jonglei Canal Project area, and to study its suitability for domestic and irrigation purposes. Such a study is carried out as a part of a general survey of the potential natural resources of the area.

Climate

The climatological data used have been collected from the climatological normals of Torit, Juba, Bor and Malakal Meteorological Stations for the period between 1941 to 1970. The location, latitude and period of records of the four stations are given in Table 1.

TABLE 1

Meteorological Stations

Station	Latitude	Longitude	Altitude (m)	Period of records years
Torit	4° 25'N	32° 33'E	625	27
Juba	4° 52'N	31° 36'E	458	30
Bor	6° 12'N	31° 33'E	423	30
Malakal	9° 33'N	31° 39'E	389	30

The dominant feature in the climate of the project area is the movement of the boundary between the northerly dry, and the southerly wet air masses with the declination of the sun. This boundary moves northwards till Lat. 19°N during the summer and returns south again during the winter. Rain is practically associated with a zone extending 800 km south of this boundary. The Jonglei Canal Project area lies within this zone characterized by heavy summer rainfall and a relatively dry winter.

The mean monthly distribution of rainfall in the four stations in the project area is shown in Table 2.

TABLE 2

Monthly rainfall distribution in mm

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec.	Year
Torit	8	16	53	99	121	115	178	141	124	102	48	23	1028
Juba	4	8	51	95	156	112	136	150	114	115	38	9	988
Bor	5	6	36	79	107	120	142	132	124	119	31	4	905
Malakal	Tr	Tr	7	21	102	109	149	167	144	82	6	Tr	787

From Table 2, the annual average rainfall in the project area ranges from about 800 mm in the north to some 1000 mm in the south and southeast. The season of heavy rain lasts for nine months extending from March to November in the south, whereas in the north it lasts for seven months extending from April to October. July and August are the wettest months in the year and about 40% of the annual precipitation falls during these two months.

The coefficient of variability of rainfall ranges from 12% at Juba to 84% at Malakal. The comparison between the average annual rainfall of the area for the periods 1931-1960 and 1941-1970 shows a slight increase in its total amount in most of the southern stations. It also shows a little decrease in the averages of July and August, which may be attributed to the limited movement of the inter-tropical zone to the north.

Most of the rainfall in the project area is of convective origin, and is derived from showers and thunder storms. The duration of thunder storms in Juba is less than one hour for 33% of the cases, 1 to 2 hours for 40% of the cases and more than 2 hours in 25% of the cases. In Malakal, the thunder storms mostly last more than one hour, and exceed 3 hours in 30% of the cases. The frequency of these long period thunder storms is highest in May and October. The mean daily maximum temperature varies between 36.8°C in Torit to 38.6°C in Malakal during February. The mean daily minimum temperature ranges from 18.1°C in Malakal to 19.5°C in Juba and Bor during December. The relative humidity ranges from the average low of 26% in Malakal and 53% in Torit during the dry season to an average height of 88% in the peak of the rainy season. The average daily evaporation from open water surface in

Juba and Malakal varies from 2.9 mm during August to 11.8 mm and 20.8 mm respectively.

The annual potential evapotranspiration calculated by Thornthwaite method for the area ranges from 1625 mm in Torit to 1800 mm at Malakal. These figures may be interpreted that on the average the Jonglei Canal Project area suffers from an annual water deficit varying from 600 mm at Torit to about 1000 mm at Malakal. However, the comparison of the amount of potential evapotranspiration versus the amount of precipitation during the peak of the rainy season (July and August) shows that the area entertains a water surplus ranging from 34 mm in the north to some 120 mm in the south. Part of this surplus becomes a surface runoff, while the rest infiltrates through the top soil and recharges the underlying groundwater body.

Topography and River System

The Jonglei Canal Project area lies mostly in the central flat plain of the Sudan which is dominantly occupied by El Sudd Region. This flat plain is bounded by relatively high terraces, locally known as dabbas, with few protruding hillocks scattered in the southern part around Juba and Torit. The altitude of the land surface ranges from 390 m in the north to 560 m in the south. The general slope is extremely flat towards the north towards Lake No and the upper reaches of the White Nile.

The project area lies within the catchment area of the Nile. The local drainage within the area is primarily to Bahr El Jebel, Bahr Ez Zaraf, Lake No and the upper reaches of the White Nile.

Bahr El Jebel is the main drainage system and the major perennial water course in the area. The river starts from Lake Albert, enters the Sudan near Nimule and proceeds to Lake No with a total length of some 1200 km.

The stretch of the river between Nimule and Rajaf, south of Juba, is a narrow fast flowing stream with occasional rapids and rocky stream bed. The average slope of the river at this portion is 1 m/km. North of Rajaf, the river starts to enter the flat plain. The average slope of the river between Rajaf and Mongalla is nearly 30 cm/km ; gradually flattening off near Mongalla. The river at Rajaf is confined to one channel with well defined banks.

Shortly before Mongalla, the southern fringe of the swamps begins. The width of the river and the swamps at Mongalla is about 3 km. Further northwards to Bor the river is never confined to one channel. The valley reaches 9 km in width and there is little open water in the swamps. North of Bor, the river is connected to many lagoons such as Lake Fagarial and Lake Papu which has an exit to the main channel of Bahr El Jebel.

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River Atem begins east of the main channel opposite to Lake Fajarial. The river continues northwards till it joins Bahr El Jebel, south of Shambe. North of Shambe, Bahr El Jebel meanders in El Sudd Region, forming many lagoons, mayas and Ox-Bows on each side, till it reaches Lake No. After reaching this lake the river turns sharply eastwards till it joins Bahr Ez Zaraf first and then River Sobat.

The average annual flow of Bahr El Jebel is 29 milliard m^3. After passing through the swamps, the River emerges with an annual average flow of 15 milliard m^3, i.e. half of its water is lost in El Sudd Region.

The sudded channels of Bahr Ez Zaraf start from a relatively high ground (Dabba) east of Bahr El Jebel, opposite Shambe. The water shed between the two rivers is extremely flat, and the Upper Zaraf was connected by Bahr El Jebel through a series of canals which drain part of the waters of El Sudd Region into Ez Zaraf. Bahr Ez Zaraf is separated from the swamps till it pours its water in the White Nile between Lake No and the mouth of River Sobat.

Subsurface Geology

The surface geological and environmental units are given in the present work which is corroborated with the subsurface geological information inferred from the rock cuttings encountered in the boreholes drilled for domestic water supply and from the geophysical surveys carried out in the area by Strojexport and Chevron Oil Co.

The major geological units encountered in the subsurface of the Jonglei Canal project area are as follows starting from the oldest : basement, Yirol Formation, Umm Rawaba Formation and the surficial deposits.

The lithologic characteristics of these units and their water-bearing properties are briefly described in Table 3.

Basement : The basement rocks outcropping in the area of investigation have been previously described in this work. It may be added that the quartzites form the course of the Nile for many kilometers. In the northern part of the project area, basement rocks including weathered acid gneiss and fresh granites have been encountered in the boreholes drilled along the burried ridges at depths ranging from 20 m to 250 m below the ground surface. It should be taken into consideration that the distribution of the basement rocks shown by Landsat imagery interpretation together with the drillhole results may imply the possible encounter of hard basement ridges in the path of the projected canal.

The basement rocks, in general, are non water-bearing except for local pockets in the weathered zone or along fractures and joint clusters.

TABLE 3

Lithology and Water-bearing Properties of the Major Geological Units Encountered in the Subsurface in Jonglei Canal Project Area

Major Geological Unit	Age	Thickness (m)	Lithology	Water-bearing Properties
Surficial Deposits	Quaternary	0—50	Sticky clay of El Sudd, loose alluvial silt, sand and gravel	The valley fill is highly porous and permeable. Depth to groundwater ranges from 0.5 to 3 m. Water quality is excellent.
Umm Rawaba Fm.	Pliocene and Pleistocene	0—350	Intercalating clays, sands and little gravel	Average low permeability. Depth to groundwater ranges from 25 to 85 m. Water quality varies from fairly saline to extremely saline.
Yirol Fm. ≈ Nubian Sandstone	Cretaceous and older	0—4000	Interbedded sandstone, mudstone and conglomerates	Aquifer is expected to be rich. The quality of water is good to fair with TDS up to 1500 ppm.
Basement	Precambrian mainly and including younger igneous bodies	Not determined	Quartzite, Acid gneiss, synite and granite	Primary permeability very low. Water occurs locally in the weathered zone and in joints and fissures. Water quality is erratic.

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Yirol Formation : This formation, associated probably with older sediments, underlies Umm Rawaba Formation in some of the deep troughs within the basins of Jonglei Canal Project area. In these troughs Yirol Formation rests unconformably either over the basement or some older sediments.

Yirol Formation was encountered in some of the deep bore-holes at depths ranging from a few meters to 370 m below the ground surface. In boreholes Nos. 3974, 3663 and 3634 some 40 m thick Yirol Formation successions consisting of sandstones with low clayey content, ironstone concretions and mudstone were encountered. The presence of Yirol Formation was also inferred from the geophysical survey carried out by Strojexport, and it has been interpreted as relatively thick beds with a higher resistivity, of more than 20 ohms, underlying the low resistivity successions of Umm Ruwaba Formation in the environs of Malakal and southwards. The thickness of these beds has been estimated to be several 100 m. The results of the seismic survey carried out by Chevron Oil Co. south of Malakal included the estimation of the thickness of the sedimentary cover, lying unconformably over the weathered surface of the basement to be in the range of several 1000 m.

Yirol Formation, in general, is predominantly formed of semiconsolidated to consolidated fine to coarse sandstone interbedded with mudstone and conglomerates. The sandstone is primarily composed of subrounded to rounded quartz grains loosely or strongly bound by a siliceous ferruginous and/or a clayey matrix. The colour of the sandstone ranges from yellow to red and brown depending on its iron oxide content. The grains are well sorted thus indicating more or less comparable conditions of deposition in extensive basins of sedimentation.

Yirol sediments fill two separate basins in the basement west of Bahr El Jebel. These sediments consist of isolated successions of mudstone and sandstone. The mudstone possesses a variety of colours ranging from violet, grey, brown to red and pink. The sediments are micaceous with few thin quartz pebbles.

Umm Rawaba Formation : This fills two basins, created by the Alpine and older tectonic events between the Ethiopian Plateau, Nuba Mountains and the southern highlands bordering Sudan with Kenya, Uganda and Zaire. The western basin occupies a large part of Bahr El Arab and continues southwards with a NW-SE trend to Duk Faiwil and further to the southeast till north of Torit. The eastern basin extends from Malakal in a N-S trend till Mongalla. The two basins intersect each other north of Jonglei, thus forming a Y shape single basin.

Umm Rawaba Formation rests unconformably either over the weathered basement surface along the burried ridges such as J. Zaraf ridge, or over Yirol Formation filling the deep troughs

within the large basins. Over much of the area underlain by Umm Ruwaba Formation the surface deposits consist of heavy clays with limestone nodules (Kanker).

The sediments of Umm Rawaba Formation are primarily of fluviatile and lacustrine origin, deposited in inland deltas and shallow lakes. These sediments consist mainly of unconsolidated sands which are sometimes pebbly clayey sands and clays. The clays are mainly buff to greyish white or greenish grey in colour. South of Malakal environs, Umm Rawaba sediments include a succession of well sorted sand at the top, whereas in the rest of area of study the clayey content dominates in most of the sediments. At Paloich north of Malakal (lat. 10° 30'N) Umm Ruwaba sediments include a succession rich in manganese.

In general, Umm Rawaba sediments are ill sorted and poorly stratified with characteristic rapid lateral and vertical facial changes. Accordingly, a permeable sandy or pebbly layer may change laterally and within a short distance to impervious clays and vice versa.

The thickness of Umm Rawaba sediments is variable, depending on its position within the basin. In the margins of the basin, or along the top of the burried basement ridges. J. Zaraf ridge, the thickness is minimal being around 100 m or less. In sunken blocks within the basin Umm Rawaba sediments may attain a thickness of over 500 m as in Borehole No. 3620 at Paloich north of Malakal.

The age of Umm Rawaba sediments is not exactly determined and their fossil content has not been identified. However, they are generally considered to be of late Pliocene and early Pleistocene age.

Surficial Deposits : These have been described previously in this work and mapped by Landsat imagery interpretation (Fig. 5). The thickness of the lateritic soils ranges from a feather edge to 30 m. The sand dunes or sand ridges are formed primarily of yellow to yellowish brown fine to coarse grained sand.

El Sudd clay plains consists of sticky heavy clay and loams rich in organic matter intercalated with a few layers of fine to medium grained sands. The valley fill deposits include a variety of unconsolidated silts, sands and gravels. Boreholes and dug wells indicate that the valley alluvium is very variable both laterally and vertically and contains thick beds and clays in close proximity. These deposits probably occur in a more or less lenticular form, hydraulically interconnected with each other. The thickness of the valley fill ranges from a few to some 25 m.

Groundwater Resources

For practical purposes, the major geological units in Jonglei Canal Project area are divided into two main categories :

1. Water-bearing units which are capable of absorbing, transmitting and yielding groundwater in sufficient quantities.
2. Non water-bearing units which do not absorb, transmit or yield groundwater in appreciable quantities.

The water-bearing units in the area include the Surficial Deposits and the Umm Ruwaba Formation/Yirol Formation aquifer system. The rocks of the Basement, in general, are considered here as non water-bearing though some of the wells drilled in Juba environs produce moderate quantities of water from the weathered zone.

Surficial Deposits : The valley fill deposits form the principal aquifer in the area underlain by the Basement rocks in Equatoria Province, water is generally obtained from a series of boreholes or shallow hand dug wells fitted with diesel operated or hand pumps. These wells are located mostly along the banks of the perennial or seasonal streams or at the wadi bed.

The depth of these wells hardly exceeds 10 m below the ground surface. However, some boreholes were drilled down to a depth of more than 20 m in Juba environs. Groundwater occurs in the sandy and gravelly successions of the Surficial Deposits under free water-table conditions. The depth of the water ranges from less than 1 m in the wadi bed to some 3 m along the high banks. The fluctuations in the watertable are rather sharp ; the water level attains its highest level shortly after the rainy season and then declines gradually during the rest of the year.

The specific capacity of the wells drilled or dug in the Surficial Deposits has never been properly tested. However, most of the wells give an appreciable and sustained yield nearly all the year round.

The groundwater tapped from the Surficial Deposits generally has an excellent quality and is fit for human and animal consumption. The amount of total dissolved solids in the water ranges between 140 ppm and 860 ppm. Water is slightly alkaline with an average of pH 8.5 and an average total hardness of 150 ppm. The most common salts dissolved in the water are sodium, and to a lesser content calcium carbonates and bicarbonates. The water does not contain any harmful or toxic ingredients.

Umm Rawaba/Yirol Formation Aquifer System : This is the main water-bearing geological unit in Southern Sudan. It underlies most of Jonglei Canal Project area. The aquifer is essentially made up of permeable sands and pebbles interbedded or intercalated with impermeable clays and silts. Due to the absence of proper aquiclude, the different water-bearing horizons are hydraulically interconnected either directly or by seepage through less permeable

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layers. Therefore, the groundwater body in each basin has a single and main water level.

Some 30 boreholes (wells) have been drilled in the discussed aquifer. The depth of these wells ranges from 40 m to 550 m below the ground surface. The regional water level in the area covered by the aquifer varies from 20 m to some 80 m below the ground surface. The output of the wells ranges between 10 to 15 m^3/h.

Groundwater occurs under free watertable conditions in the aquifer, and it has more or less a main regional water level. Mild local artesian conditions sometimes occur where the permeable water-bearing beds are found in a lenticular form surrounded by highly impermeable silts and clays.

The seasonal or permanent regional fluctuations in the watertable of the aquifer have never been monitored. Recent measurements of the depth of water in Borehole No. 6430 at Malakal show a slight but steady decline of 12 cm in the watertable during the period between February and the beginning of May. Such decline may be attributed to the seasonal fluctuations in the water level of the White Nile. The hydraulic continuity between the groundwater body and the perennial water courses in the area is evident from the high tritium content (between 229 and 414 Tu) of the groundwater of the tube wells along the banks of the White Nile. The fluctuations in the piezometric surface of the groundwater in the aquifer, at large, are expected to be minimal and insignificant because of its large areal extent and high storage capacity.

With the exception of few points at the rim of the major basin or along some of the burried basement ridges, the thickness of the aquifer in question is not fully known. At these points, the thickness of the aquifer ranges from 70 m to 150 m. In the deep troughs of the basin the whole thickness of the aquifer has not been penetrated and it is estimated by geophysical methods to be in the order of several 100 m or even 1000 m.

Hydrologic Properties of the Aquifer : The sediments of the Umm Rawaba Formation/Yirol Formation aquifer system below the watertable, vary in their storage, transmitting and drainage capabilities. This is attributed to the lateral and vertical variations in the lithologic characters of the water-bearing materials.

The wells drilled in the Jonglei Canal Project area have never been properly treated by pumping in order to study the hydrologic characteristics of the aquifer. The only tests carried out were by a bailer, for several hours, to determine productivity of these wells. However, from those bailer tests, and from the lithologic description of the water-bearing materials encountered from these wells, the following tentative transmissivity values of the aquifer have been estimated in Table 4.

TABLE 4

The Coefficient of Transmissivity of Umm Rawaba Formation/Yirol Formation Aquifer System

Well No.	Location	Coefficient of Transmissivity
3640	Malakal	3,300 m^2/day
3666	Liying Scheme	14,900 m^2/day
3656	Oriang	13,000 m^2/day
3636	Dolieb Hill	17,200 m^2/day
3657	Ayod	17,200 m^2/day

According to these volumes the average coefficient of permeability of the aquifer is estimated to be ranging from 0.13 m/day to 0.029 m/day. From the lithologic logs of the wells and from the bailer tests carried on them, the coefficient of storage has been estimated to be 10^{-2} to 10^{-3} which indicates mild artesian conditions.

The indicative watertable contour map (Fig. 7) shows that the groundwater movement in the aquifer is from south to north, i.e. in the same direction of the surface water drainage of the area. The map also shows that the aquifer is receiving an appreciable amount of recharge from the northern piedmont of the basement in Equatoria Province and from the southern slopes of the Nuba Mountains.

The relationship between the groundwater body and the perennial streams of the area is not clearly identified, however, from the shape of the watertable contours in the map it looks as if the stretch of Bahr El Jebel from Mongalla to north of Bor is acting as an effluent stream recharging the groundwater reservoir. North of Jonglei, in El Sudd Region proper, both the surface and groundwater bodies emerge together and crop out in the form of swamps and marshes covering the triangle between Bahr El Jebel and Bahr Ez Zaraf. The watertable contours indicate that Bahr El Jebel north of Jonglei is acting like an influent stream where the river is receiving water from the aquifer. The contours indicate also that El Sudd Region is acting like a funnel into which all the surface and groundwater are drained. Jebel Ez Zaraf ridge is acting like a groundwater divide which separates the water drained into El Sudd Region and that moving northwards along the White Nile.

The average slope of the watertable in the aquifer system upstream El Sudd Region is some 0.4 m/km. This gradient falls gradually till it becomes extremely flat in El Sudd Region south of Lake No. In this part, the movement of groundwater is almost nil and the groundwater body becomes stagnant, and it contributes to the marshes and swamps covering this part.

The aquifer system underlies some 31,000 km^2 of the project area. Despite the quality of the water, all the wells drilled within the area of the aquifer were productive. However, their productivity varies according to the lateral or vertical variations in the hydrogeologic properties of the water-bearing materials forming the aquifer.

The groundwater in storage within any aquifer is generally estimated by multiplying the volume of saturated sediments by their coefficient of storage or their specific yield. The minimum thickness of the aquifer, so far known, is some 20 m, whereas the maximum may reach several 1000 m. The coefficient of storage has been estimated to be ranging from 10^{-2} to 10^{-3}. Accordingly, the groundwater in storage in each meter thickness of the aquifer will be in the order of 81 to 810 million m^3 of water. This also means that assuming no recharge, which is not the case, then one has to draw a volume of water ranging between 81 to 810 million m^3 of water in order to lower the present watertable by one meter. This definitely indicates the large capability of the aquifer as a source of water either for domestic use or for irrigation purposes once the projected canal is constructed.

Recharge to the aquifer can be secured from different sources such as direct precipitation, effluent seepage from surface runoff and through subsurface inflow from the basement piedmonts surrounding the aquifer.

The Jonglei Canal Project area enjoys an average water surplus in the order of 75 mm during July and August which is the peak of the rainy season. Such surplus is equivalent to some 6000 million m^3 of water over the area underlain by the aquifer in the Jonglei Canal Project area. Assuming that only 10% of this amount of water seeps down to recharge the underlying aquifer, whereas the remaining water flows either as surface runoff or is kept as a soil moisture in the vadoze zone. Therefore, the amount of recharge from direct precipitation to the aquifer system in Jonglei Canal Project area is estimated to be 600 million m^3/annum.

The amount of subsurface recharge to the aquifer system from the southern basement piedmont can be estimated using Darcy's Equation as follows :

$$Q = TIL \text{ where}$$

Q : amount of subsurface inflow in m^3/day
T : average transmissivity of the aquifer
I : the hydraulic gradient
L : the length of the aquifer

Accordingly, the daily subsurface inflow will be

$Q : 13{,}000 \times 0.0004 \times 75{,}000 = 390{,}000$ m^3/day.

This is equivalent to some 140 million m^3/annum.

Recent recharge to the aquifer system has been confirmed from the tritium analysis carried on the groundwater of some of the tube wells along the White Nile near and north of Malakal. The results of these analyses are shown in Table 5.

TABLE 5

Tritium Content of the Groundwater in Malakal Environs (after Strojexport)

Borehole No.	Location	Latitude	Longitude	Tritium Content (Tu)
3978	Lelo	9°37'	31°32'	229
3669	Akaraweng	9°42'	32°20'	278
3663	Akoke	9°45'	32°15'	259
3628	Rom	11°45'	32°45'	414

It is evident that the groundwater in storage plus the amount recharged every year is, by far, greater than the present and future demands for domestic water in the area. It also encourages, whenever the quality permits, the use of these groundwater resources to grow, under supplementary irrigation, some high value cash crops which can contribute to the economic welfare of the area.

On the basis of chemical analyses carried out on some groundwater samples obtained from the tube wells drilled in the concerned aquifer system in Jonglei Canal Project area, a groundwater iso-salinity contour map was constructed for the aquifer (Fig. 8). The salinity values are expressed in ppm of the total dissolved solids (TDS). The complete chemical analysis of the groundwater of some of the wells is shown in Table 6.

The iso-salinity contour map further confirms the idea that the aquifer system is receiving appreciable amounts of fresh water recharge from the basement piedment around the aquifer. It also shows that the amount of T.D.S. increases in the direction of movement of groundwater within the aquifer.

From the map (Fig. 8) it is evident that the aquifer includes two hydrogeochemical zones weakly connected or even rather separated by Bahr Ez Zaraf basement ridge. The northern zone covers the environs of Malakal basin, and the groundwater in this zone is extremely hard and highly mineralized. The TDS varies between 2000 ppm and over 6000 ppm. The salinity decreases in every direction away from Malakal. The relationship between the salinity of the aquifer and its depth is more clearly known as most of the drilled wells in Malakal basin have shallow depths and were all finished within the highly mineralized Umm Rawaba segment of

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the aquifer. Moreover, it has been noted that the deep wells always have a better quality water than the shallow ones drilled in the same locality, e.g., Well No. 3631, total depth 133 m, TDS 5270 ppm and Well No. 3660, total depth 344 m, TDS 2300 ppm. The relative freshness of the groundwater in the deep wells may be attributed to the possibility of deriving part of their water from the less mineralized Yirol segment of the aquifer.

The non carbonate alkalies (primary hardness) dominate the dissolved mineral salts in the groundwater tapped from the northern zone of the aquifer. More than 60% of these salts are in the form of sodium sulphate and sodium chloride. The cause of the highly mineralized groundwater in the northern zone of the aquifer is not fully understood. However, saline water is frequently tapped from the Umm Rawaba aquifers in different parts of the Sudan. The main reason for the salinity is attributed to their mode of deposition, where some of the water-bearing material was deposited in closed shallow lakes under semi-arid conditions.

The southern zone covers the rest of the aquifer system. Groundwater tapped from this zone is generally fresh with TDS always less than 1000 ppm. The earth alkalies and alkali carbonates and bicarbonates, and secondary permeability dominate the dissolved salts in the groundwater at the rim of the aquifer. About 50% of these salts are in the form of calcium, magnesium and sodium carbonates and bicarbonates. As the groundwater moves to the center of the basin, these salts gradually give up to the non carbonate alkalies and the water gets more saline.

Suitability of Groundwater for Domestic Use : The general specifications of drinking water in the Sudan as adopted by the Ministry of Health are as follows :

1. Water should be free from colour, turbidity and any unpleasant odour or taste.

2. The TDS should not exceed 2500 ppm, however, for cattle and other livestock water up to 7000 ppm can be used.

3. The concentration of certain ions should not exceed the harmful limits such as :

Constituent	Upper limit in ppm
F	1.5
Pb	0.1
As	0.05
Se	0.05
Cr^{++++++}	0.05

These limits are mandatory and excessive concentrations may constitute basis for the rejection of the whole supply.

Other limits which are less strict are :

Mg^{++}	125	ppm
Cl^{-}	750	"
SO_4^{--}	500	"
NO_3^{-}	50	"
Ammoniacal Nitrogens as N	0.06	"
Albuminoid Nitrogen as N	0.1	"
Total Alkalinity as $CaCO_3$	150	"

The human and animal population of Jonglei Canal Project area are depending on the groundwater tapped from the aquifer system for their drinking and other domestic purposes for most of the year. Some 30 tube wells fitted with piston pumps and diesel motors are tapping their water from the aquifer. From the available chemical analysis, it is clear that, with the exception of the environs of Malakal, the groundwater tapped from the aquifer system is fresh and contains lower amounts of salts than those quoted in the above specifications. All the other iron concentrations are also far below the harmful limit. Accordingly, such water is fit for human and animal consumption, as well as for other domestic uses.

Suitability of Groundwater for Irrigation : Groundwater is not currently used for irrigation in the Jonglei Canal Project area. However, the possibility of using it for supplementary or even for full irrigation of the reclaimed land after the construction of the projected canal should not be excluded.

The assessment of the suitability of water for irrigation usually takes into consideration the following criteria :

1. The amount of total dissolved salts expressed in the form of electrical conductivity, measured in μ mohs/cm.

2. The sodium absorption ration (S.A.R.).

3. The toxic level of individual ions such as boron, selenium, magnesium and sodium.

From the chemical analysis of the groundwater of the southern zone of Umm Rawaba Formation/Yirol Formation aquifer system, it is clear that the electrical conductivity of most of the samples is lower than 750 μ mohs/cm. Their S.A.R. ranges from 1.28 to about 4, therefore, such waters are classified as good to excellent (from C2S1 to C1S1) as to their suitability for irrigation. These waters can be used for various crops and soils without fear of salinity or alkalinity hazard.

The groundwater of the northern zone of the aquifer system is highly mineralized, with a specific conductance always over 1000 μ mohs/cm. Their S.A.R. ranges from 8.8 to 15.5. This classifies them as C3S2 or worse, i.e., fair to poor waters for irrigation.

The fair waters can only be used for crops with moderate to high salt tolerance and for coarse textured soil.

Cost of Water Provision : The estimation of accurate costs for drilling and construction of water stations in Jonglei Canal Project area is rather difficult because the costs change drastically from year to year. A groundwater station normally consists of one or two tube wells fitted with reciprocating diesel powered piston pumps, elevated 5 m^3 steel tank, four livestock troughs, and six taps for domestic water supply. The common diameter of tube wells for domestic supply is 150 mm, always installed with API plain and slotted casings.

The average cost for drilling in Southern Sudan is estimated to be $ 100/m. The cost of the pump and other installations in the water station may sum up to $ 20,000. Accordingly, a water station with one tube well of a depth of 200 m will cost $ 40,000, while a station with twin wells is estimated to cost about $ 60,000.

TABLE 6. — **Chemical Analysis of Groundwater from Equatoria Wells and Upper Nile**

Well No.	Location	Lat. N	Long. E	pH	T.D.S.	T.H.	T. Alk.	E. Alk.
3671	Juba	4°50'	31°30'	8.8	400	220	350	134
3690	Lago	4°00'	30°10'	7.9	140	48	100	55
3691	Lorri	4°47'	31°39'	7.8	240	80	100	20
3691	Ianya	3°31'	30°50'	8.1	300	140	180	42
3693	Loka	4°17'	31°10'	8.3	230	100	150	53
3950	Juba	4°50'	31°30'	8.6	620	180	300	127
3636	Doleib Hill	9°20'	31°35'	7.3	6420	3640	250	Nil
3643	Malakal	9°35	31°40'	8.8	2460	400	830	460
3646	Lake Feng.	7°12'	31°57'	8.5	350	124	280	165
3449	Duk Fobit	7°45'	31°25'	8.2	185	75	120	45
6650	Duk Faiwi	7°30'	31°25'	8.0	120	50	90	40
3651	Kongor	7°29'	31°22'	8.0	780	255	500	260
3654	Anyad	6°20'	31°50'	8.6	430	180	350	180
3655	Balawang	8°48'	31°32'	7.8	4120	1200	140	Nil
3656	Oryang	9°05	31°31'	8.0	2060	720	150	Nil
3657	Ayod	8°07'	31°26'	8.0	170	68	100	34
3658	Magogh	8°25'	31°15'	8.7	1080	248	330	87
3660	Mading	9°10'	32°11'	8.1	2300	800	370	Nil
3666	Lyria	9°22'	31°42'	7.5	5800	2660	340	Nil
3678	Lelo	9°37'	31°32'	8.1	1400	165	590	450
6430	Malakal	9°35'	31°40'	8.2	5400	1800	500	Nil
6929	Bor	6°15'	31°35'	8.8	340	120	290	180

T.D.S. : Total Dissolved Solides in ppm.

T.H. : Total Hardness as Ca Co_3 in ppm.

T.Alk. : Total Alkalinity as Ca CO_3 in ppm.

E.Alk. : Excess Alkalinity as Na_2CO_3 in ppm.

Ca, Mg, Na, K, Fe, Cl, SO_4, NO_3, N_2 and F values in ppm.

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Ca	Mg	Na	K	Fe	Cl	SO_4	NO_3	NO_2	F	Aquifer	Remarks
51	23	?	—	—	20	7	15	Nil	1.3	S	Fit
8	7	?	—	—	8	20	2	0.4	0.4	S	Fit
20	10	?	—	—	10	15	Nil	Nil	0.8	S	Fit
48	5	—	—	—	16	84	2	2	0.4	S	Fit
27	8	—	—	—	16	54	1	Nil	0.2	S	Fit
24	29	75	7.4	—	70	20	8	Nil	1.5	S	Fit
632	25	?	?	?	1600	2580	50	2	2	UR/Y	Unfit
92	41	?	?	?	130	960	Nil	Nil	1	UR/Y	Fit
32	11	?	?	?	8	20	Nil	Nil	0.4	UR/Y	Fit
20	10	?	?	?	10	5	Nil	Nil	0.5	UR/Y	Fit
15	5	?	?	?	10	15	Nil	Nil	0.9	UR/Y	Fit
60	25	?	?	?	50	80	7.5	Nil	0.6	UR/Y	Fit
35	22	?	?	?	20	20	2.5	Nil	0.3	UR/Y	Fit
40	145	?	?	?	440	330	Nil	Nil	0.3	UR/Y	Unfit
175	70	?	?	?	350	940	Nil	Nil	0.2	UR/Y	Unfit
17	6	?	?	?	12	47	il	Nil	0.4	UR/Y	fit
67	19	?	?	?	75	480	1.25	Nil	0.4	UR/Y	Fit
176	87	?	?	?	380	850	2.5	2.5	0.3	UR/Y	Unfit
616	258	?	?	?	1680	1870	10	20	0.3	UR/Y	Unfit
30	20	?	?	?	80	495	12	—	0.7	UR/Y	Fit
415	190	125	30	—	380	2915	110	0.14	Nil	UR/Y	Unfit
38	6	100	77	—	16	21	Nil	Nil	0.3	UR/Y	Fit

Aquifer S : Surficial Deposits

Aquifer UR/Y: Um Rawaba Formation/ Yirol Formation Aquifer Syste n

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BOREHOLE No. 3636

Location : Doleib Hill
Total Depth : 180 m
Depth to Water : 40 m

Log Description

Depth (m)	Lithology
Surficial Deposits :	
0—3	Clay, highly silty, yellowish grey.
Umm Rawaba Formation :	
3—58	Clay, slightly silty, dark grey with kanker nodules.
58—92	Clay, highly sandy, greyish with ironstone and kanker nodules.
92—100	Sands, highly clayey, fine to coarse grained, moderately sorted, yellowish.
100—138	Clay, low sandy content, yellowish grey.
138—158	Sand, highly clayey, well sorted with ironstone concretions.
158—178	Sands, low clay content, fine to medium rather well sorted, greyish yellow.
178—180	Clay, low sand content, with dark ironstone concretions.

BOREHOLE No. 3651

Location : Kongor
Total Depth : 125 m
Depth to Water : 29 m
Output : 5.5 m^3/h

Log Description

Depth (m)	Lithology
Surficial Deposits :	
0—3	Clayey sand, fine to coarse grained, subangular to subrounded, moderately sorted.
Umm Rawaba Formation :	
3—10	Sandy clay, yellowish.
10—22	Clayey sand, subangular to subrounded, moderately sorted.
22—30	Clay, highly sandy, greyish yellow.
30—125	Sands, low clayey content, fine to coarse grained, subangular to subrounded.

BOREHOLE No. 3652

Location : Malakal
Total Depth : 70 m
Depth to Water : 25 m
Output : 5.5 m^3/h

Log Description

Depth (m)	Lithology
0—30	Clay, with low sandy content and some kanker nodules.
30—30	Sandy clay, grey with pale brown patches.
35—40	Clayey sand, medium to coarse grained, moderately sorted, pale to yellowish.
40—60	Sandy clay with some iron nodules.
60—65	Clayey sand, coarse grained, moderately sorted with some iron concretions.
65—70	Sandy clay, pale brown with ironstone nodules.

BOREHOLE No. 3658

Location : Magogh
Total Depth : 330 m
Depth to Water : 82 m
Output : 5.5 m^3/h

Log Description

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Depth (m)	Lithology
Surficial Deposits :	
0—2	Sands, highly clayey.
Umm Rawaba Formation :	
2—8	Sands, low clayey content, fine to coarse grained, moderately sorted, yellowish in colour.
8—33	Clay, slightly sandy, greyish to yellowish.
33—82	Mudstone, slightly sandy, hard with ironstone concretions.
82—270	Clay, slightly silty, pale brown, with ironstone concretions.
270—290	Clay with a higher content of fine to coarse grained sand, greenish grey with brown spots.
290—330	Sands, highly clayey, medium to coarse with some pebbles and weathered basement fragments.

BOREHOLE No. 3978

Location : Lelo
Total Depth : 113 m
Depth to Water : 44 m

Log Description

Depth (m)	Lithology
Surficial Deposits :	
0—14	Clay, slightly sandy, earthy in colour, with white kanker nodules.
Umm Rawaba Formation :	
14—56	Clay, slightly sandy, greyish in colour.
56—60	Sand, slightly clayey, fine to coarse poorly sorted, brownish grey.
60—70	Clay, low sandy content, pale with grey patches, with ironstone concretions.
70—73	Sand, silty, poorly sorted, subangular to subrounded grains, yellowish.
73—75	Clay, silty, greyish brown, with few pebbles and fragments of ferruginous sandstone.
75—110	Sands, slightly clayey, fine to coarse.
110—113	Clay, slightly sandy, grey with white spots.

BOREHOLE No. 3691

Location : Lorri, Equatoria
Total Depth : 25 m
Depth to Water : 3 m

Log Description

Depth (m)	Lithology
Surficial Deposits :	
0—1.5	Clay, sandy, brown.
1.5—7	Sand, fine to coarse.
7—8	Sand, clayey, yellow.
8—9	Clay, sticky, dark grey.
9—18.5	Sand, medium to very coarse, rounded to subrounded.
18.5—22	Sand, clayey, rounded to subrounded.
22—25	Weathered basement.

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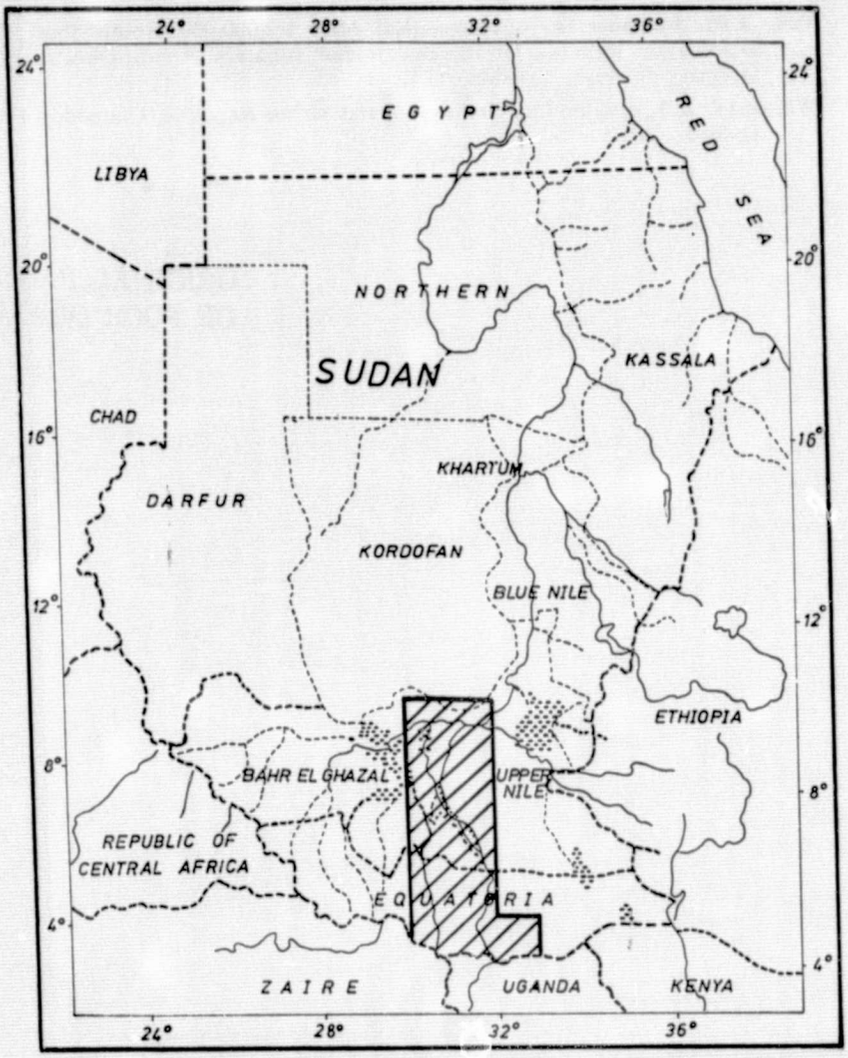


FIG .1. LOCATION MAP OF JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN

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الملخص

ينبع نهر النيل من اواسط افريقيا حيث يتخذ اسم نيل فيكتوريا ، ثم يصبح اسمه نيل البرت عند الطرف الشرقى لبحيرة االبرت ، وحر الجبل عند نمولى عند حدود السودان الجنوبية . وعند منطقة السدود فى جنوب السودان يدخل بحر الجبل سهل غرينى شبه منبسط ، حيث يصبح مجرى النهر كثير التشعب ، وحيث تنتشر المستنقعات التى تغطيها النباتات تغطية كثيرة . وهناك يكفى المجرى الرئيسى لبحر الجبل لحمل مياه تصرف النهر حينما يكون منسوب المياه منخفضا . الا انه عندما يرتفع منسوب المياه فان بحر الجبل يفيض على جوانبه مما يؤدى الى فقدان نسبة كبيرة من المياه عن طريق التسرب او البخر او النتح .

ويزيد تصرف بحر الجبل عند مونجالا شهريا عن ٢٠٠٠ مليون متر مكعب خلال اشهر مايو ، يونيو ،: يوليو ، اغسطس ، سبتمبر ، اكتوبر ، نوفمبر ، وديسمبر ، اما خلال اشهر : يناير ، فبراير ،: مارس ، وابريل فان التصرف الشهرى لبحر الجبل يقل عن ٢٠٠٠ مليون متر مكعب .
ويقدر الفاقد السنوى للمياه عند بحر الجبل بجنوب السودان بزهاء ١٢٢٥٠ مليون متر مكعب .وقد جرت دراسات عديدة للتغلب على فقدان المياه ببحر الجبل ، ويعتبر مشروع قناة جونجلى الذى يتمثل فى حفر قناة طولها حوالى ٢٨٠ كيلومتر تربط جونجلى على بحر الجبل بملاكال على النيل الابيض من المشروعات التى حازت القبول فى صدد حل هذه المشكلة .

ويكمن الحل الامثل للمسح والدراسة الاقليمية لتلك المنطقة الشاسعة لمشروع قناة جونجلى فى استخدام صور القمر الصناعى لاندسات ، ويبدو ذلك جليا بالنسبة لصعوبة ارتياد المنطقة وعلى الاخص اثناء فصل المطر الطويل . وقد تم تنفيذ عمليات المسح والدراسة بالاستعانة بصور القمر الصناعى لاندساتالماخوذة اثناء فصل الجفاف واثناء فصل المطر مع استخدام الطيران الاستطلاعى ، العمل الحقلى الأرضى على الطرق والدروب التى يمكن عبورها ، واجراء التحاليل المعملية المستفيضة . وقد قدم فى هذا الجزء من عمليات المسح والدراسة خرائط التكاوين الجيولوجية والبيئية ، التراكيب الخطية ، كثافة التراكيب الخطية ، الصرف الصحى ، والمياه السطحية والأرضية . وبذلك ادى استخدام صور القمر الصناعى لاندسات فى وقت قصير الى وضع صورة اقليمية لتلك المنطقة الفريدة فى نوعها والتى تغطى ١٦٥٠٠٠ كيلومتر مربع .

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حقوق الطبع محفوظة ١٩٧٧ ـ لمركز الاستشعار من البعد

جميع الحقوق محفوظة ، غير مصرح بنقل أو استخدام اى جزء من هذا التقرير أو الخرائط باى طريقة من طرق التصوير الضوئى أو الالكترونى الا بتصريح كتابى من الناشر .

رقم الايداع بدار الكتب المصرية ـ ١٩٧٨/٣٤٣٠

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دراسة اقليمية للجيولوجيا والجيومورفولوجيا والتراكيب والصرف والهيدرولوجيا بمنطقة بحر الجبل جنوب السودان

منطقة مشروع قناة جونجلى من الأقمار الصناعية لاندسات

الأستاذ الدكتور الشاذلى محمد الشاذلى

رئيس هيئة المواد النووية ومدير المجموعة الجيولوجية
بمركز الاستشعار من البعد ، القاهرة ، مصر

الأستاذ الدكتور محمد أحمد عبد الهادى

أستاذ الهندسة المدنية بجامعة ولاية أوكلاهوما بالولايات المتحدة
ومدير مركز الاستشعار من البعد ، القاهرة ، مصر

الجيولوجيا والجيومورفولوجيا والتراكيب والصرف
دكتور محمد عبد الرازق الغوابى
دكتور عبد العاطى بدر سلمان
دكتور ابراهيم على القصاص
دكتور سمير محمد خواسك
جيولوجى ماجد محمد الركايبى
دكتور حسن الامين

باحثون بهيئة المواد النووية ومركز الاستشعار من البعد
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الهيدرولوجيا
الأستاذ الدكتور محمد محمد الشاذلى

أستاذ باحث بمعهد الصحراء ومركز الاستشعار من البعد
القاهرة ، مصر

جيولوجى ولسن اسكندر

المركز القومى للبحوث ، الخرطوم ، السودان

الناشر

مركز الاستشعار من البعد ● أكاديمية البحث العلمى والتكنولوجيا

١٠١ شارع القصر العينى بالقاهرة ج.م.ع

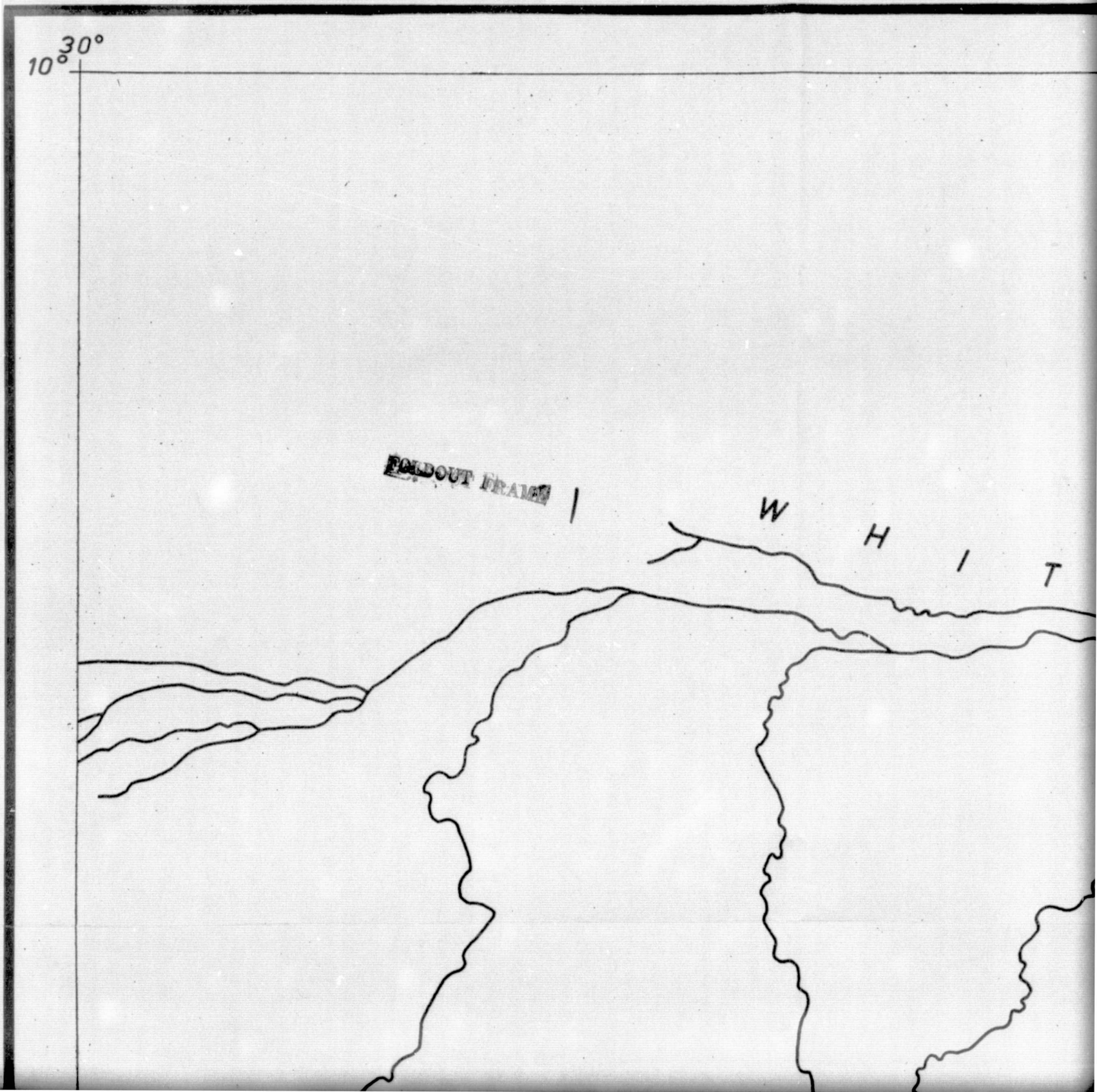
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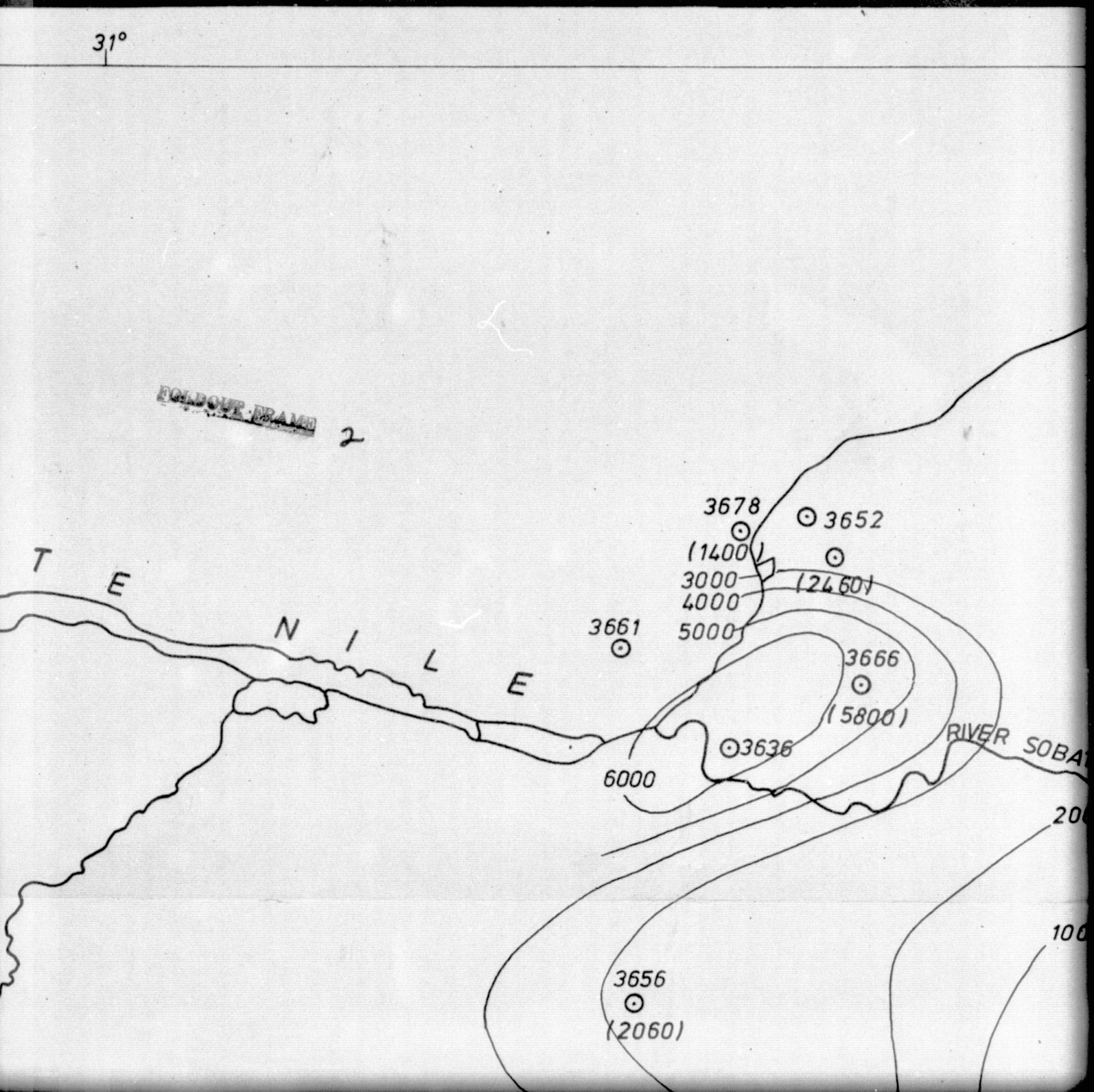
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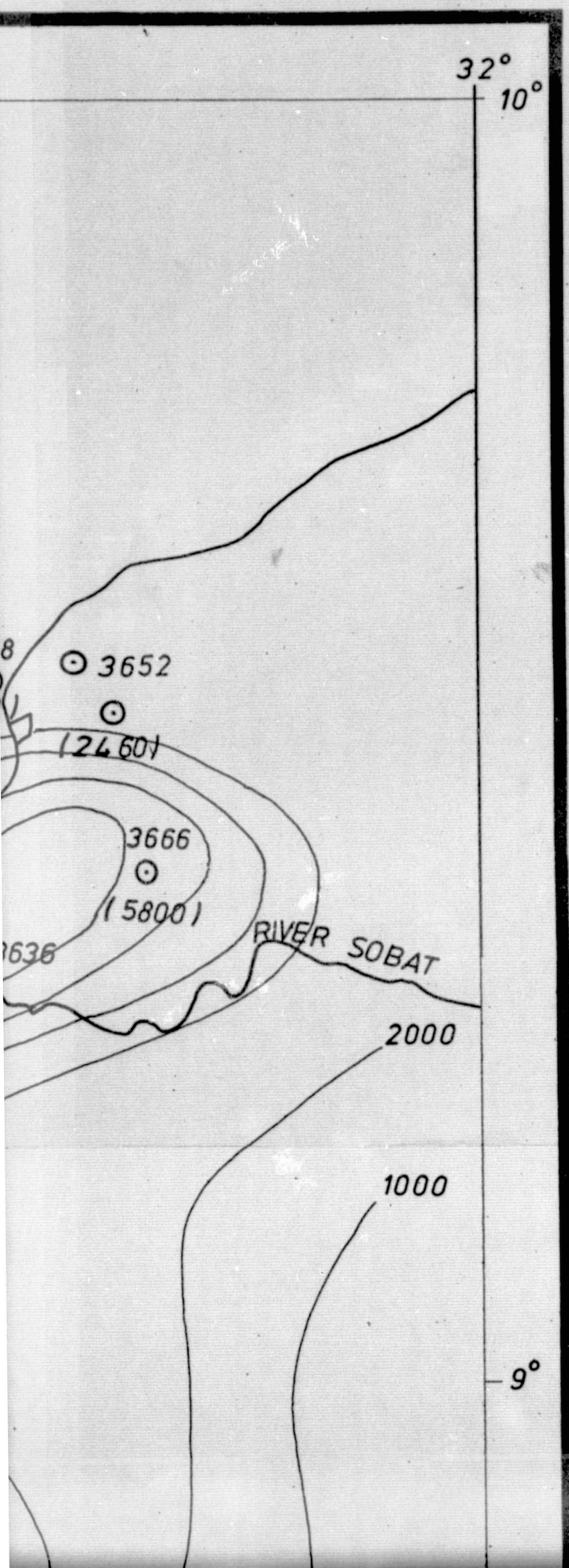
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CAIRO - EGYPT



NOLOGY


31°
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MINISTRY OF IRRIGATION,
ARAB REPUBLIC OF EGYPT

THE PERMANENT JOINT
COMMISSION FOR NIL

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OF IRRIGATION,
PUBLIC OF EGYPT

MINISTRY OF IRRIGATION,
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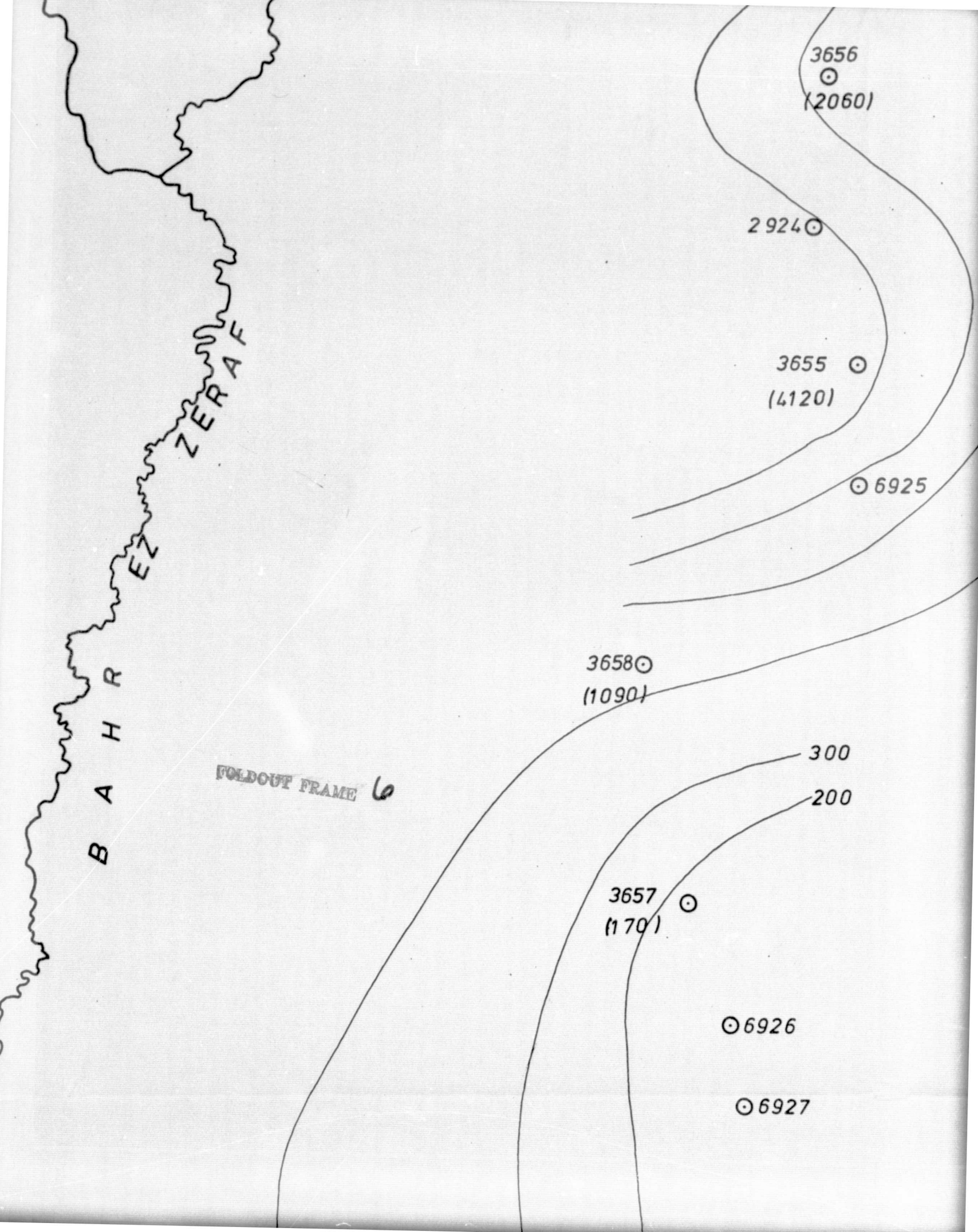
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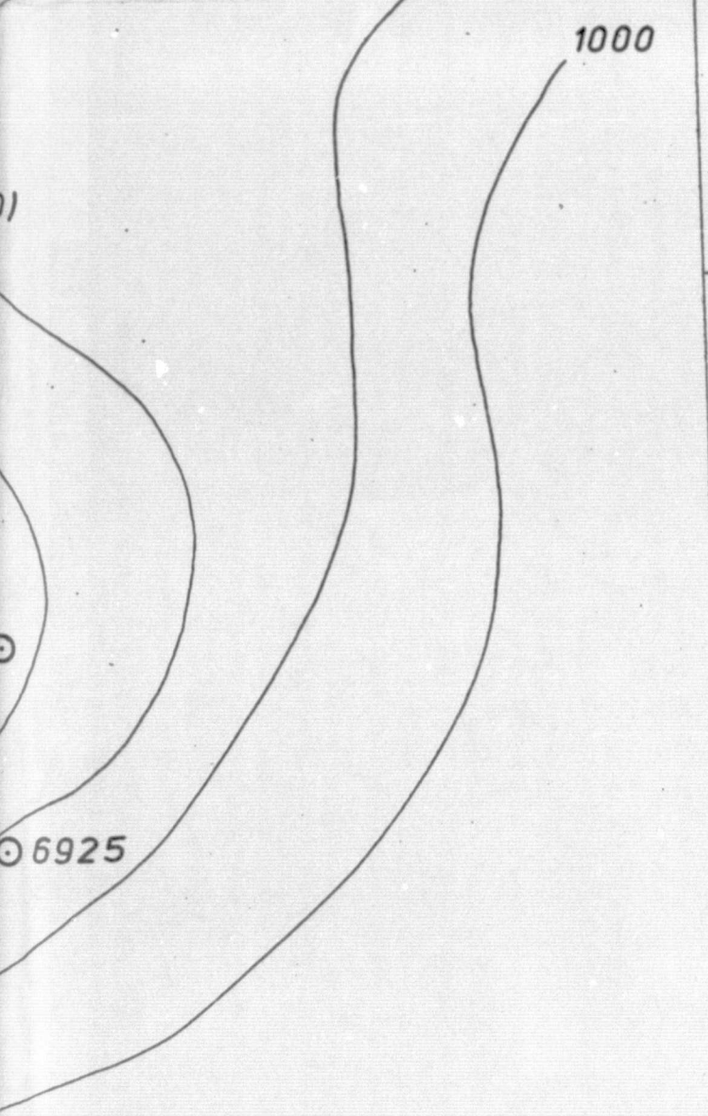
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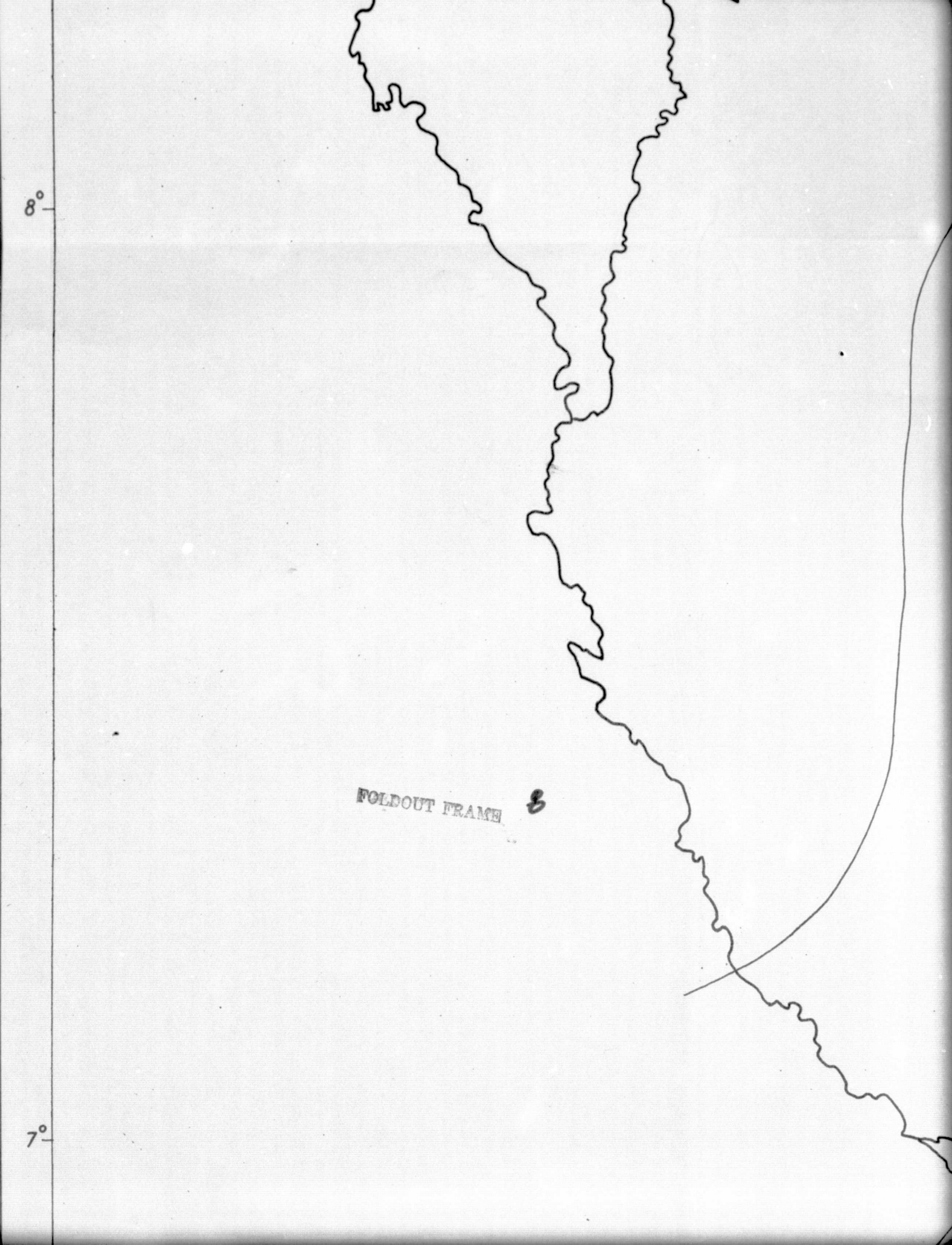
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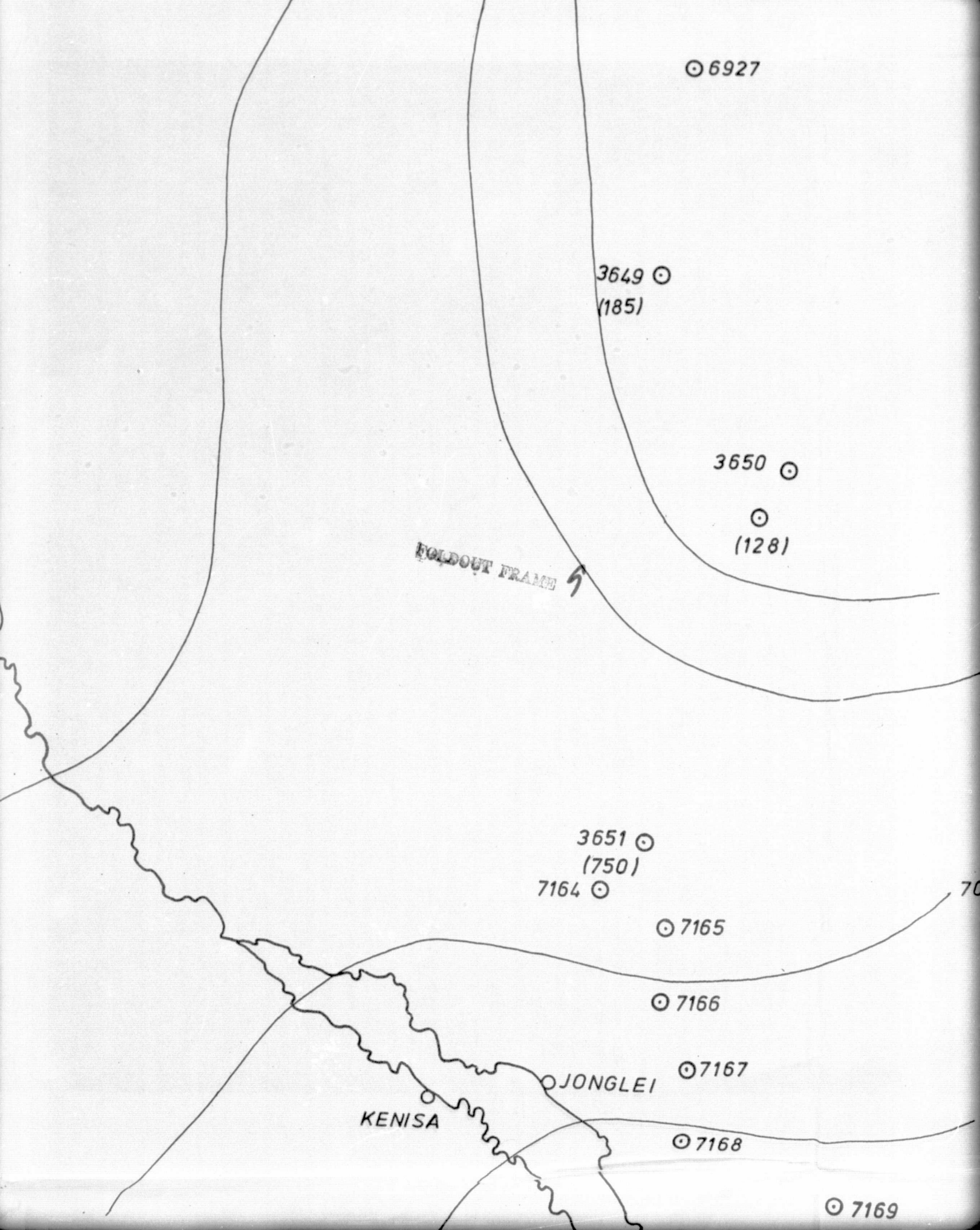
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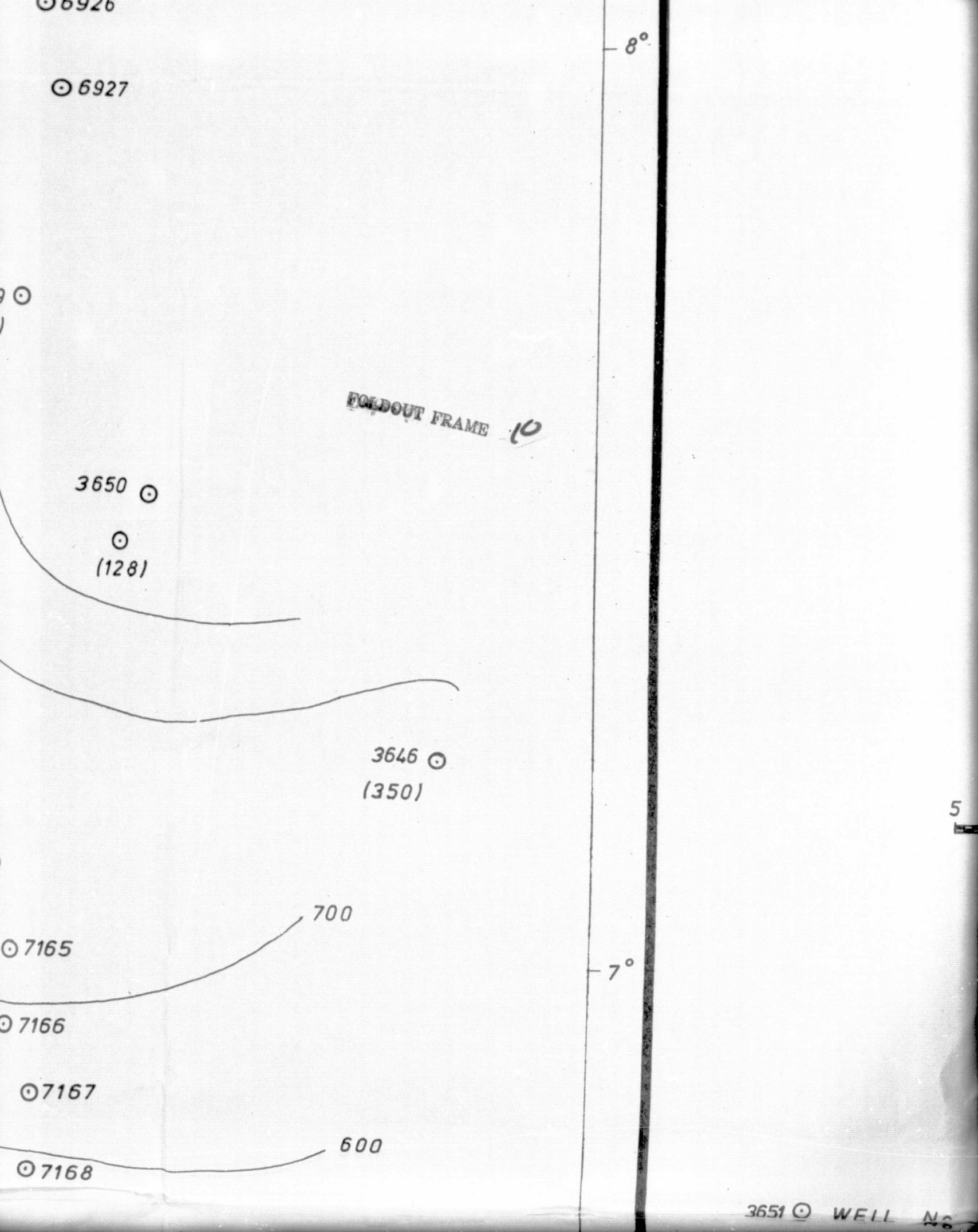
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(780) TOTAL SALINITY IN ppm

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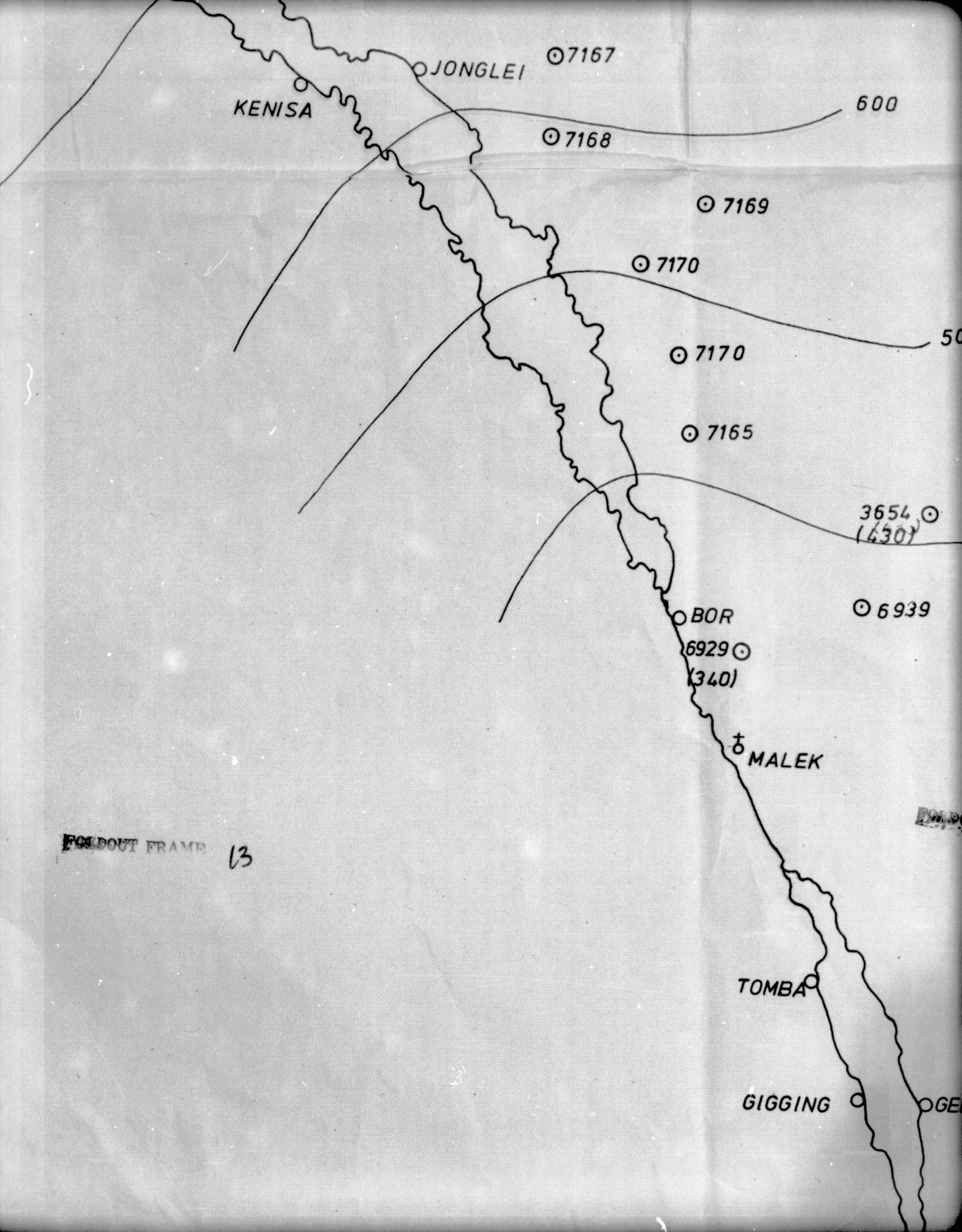
CITIES AND TOWNS

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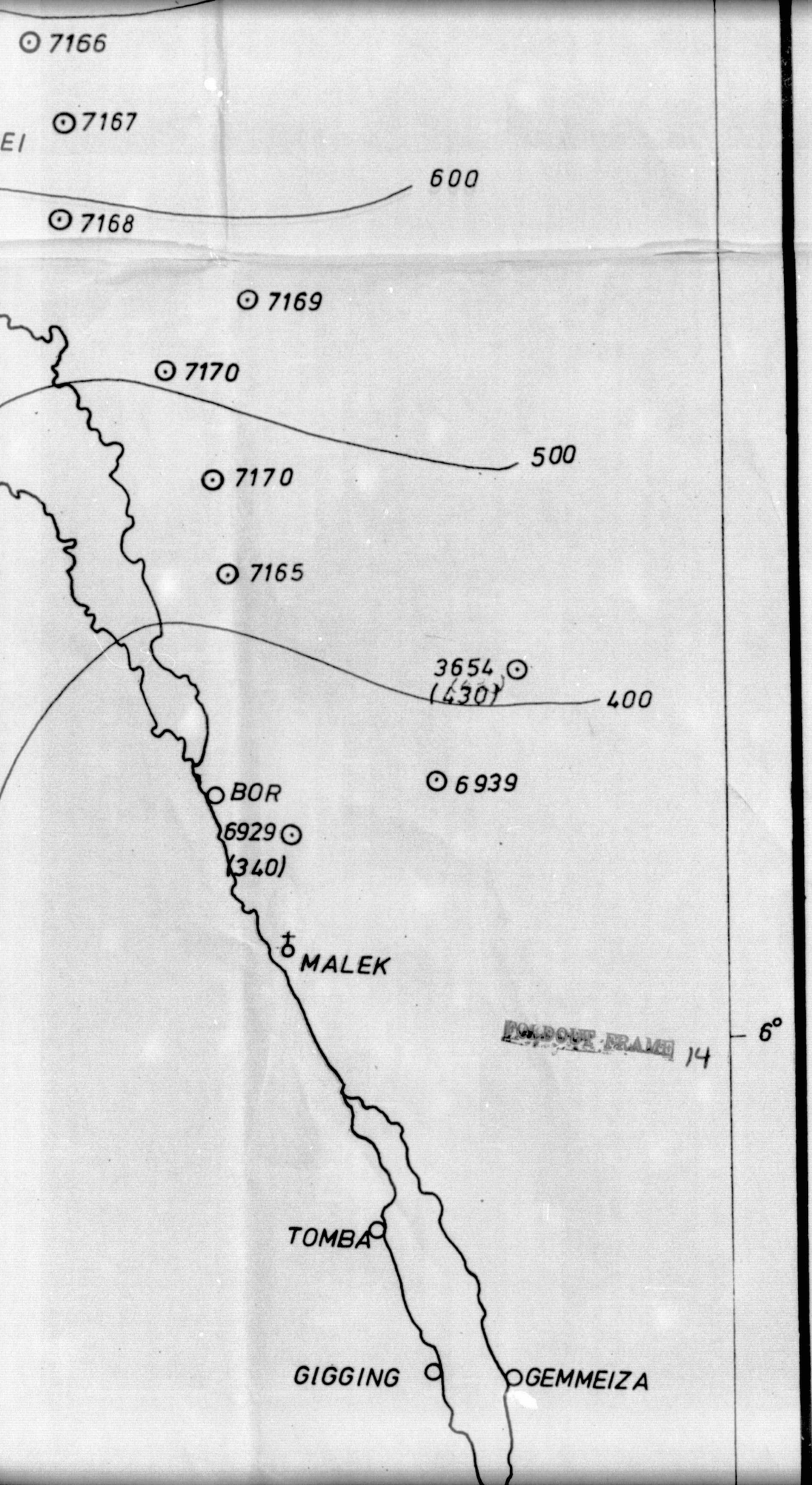
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3651 ⊙ WELL

(780) TOTAL SALINITY IN ppm

600 ISO - SALINITY CONTOUR LINE IN ppm

 CITIES AND TOWNS

○ SETTLEMENTS AND SMALL TOWNS

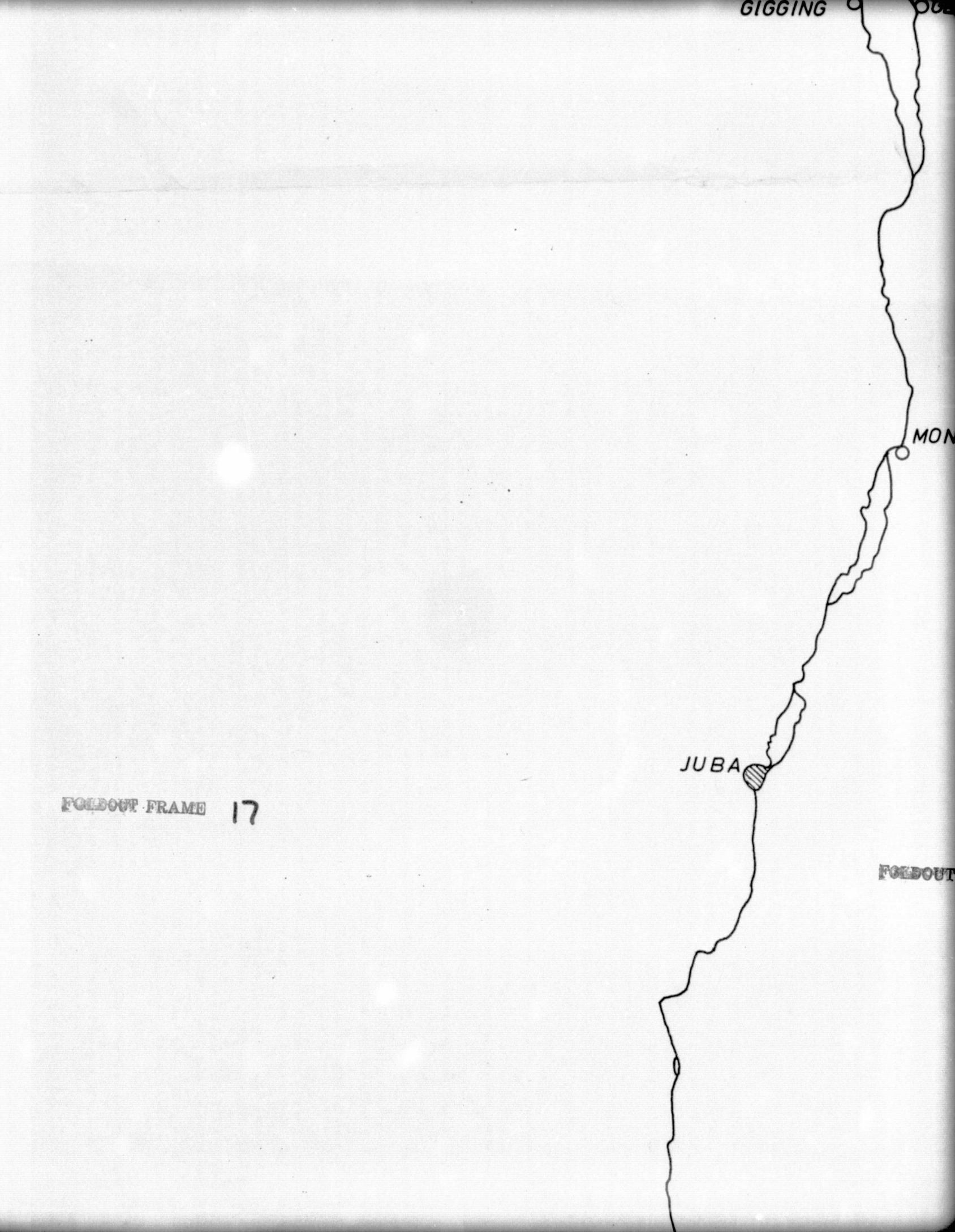
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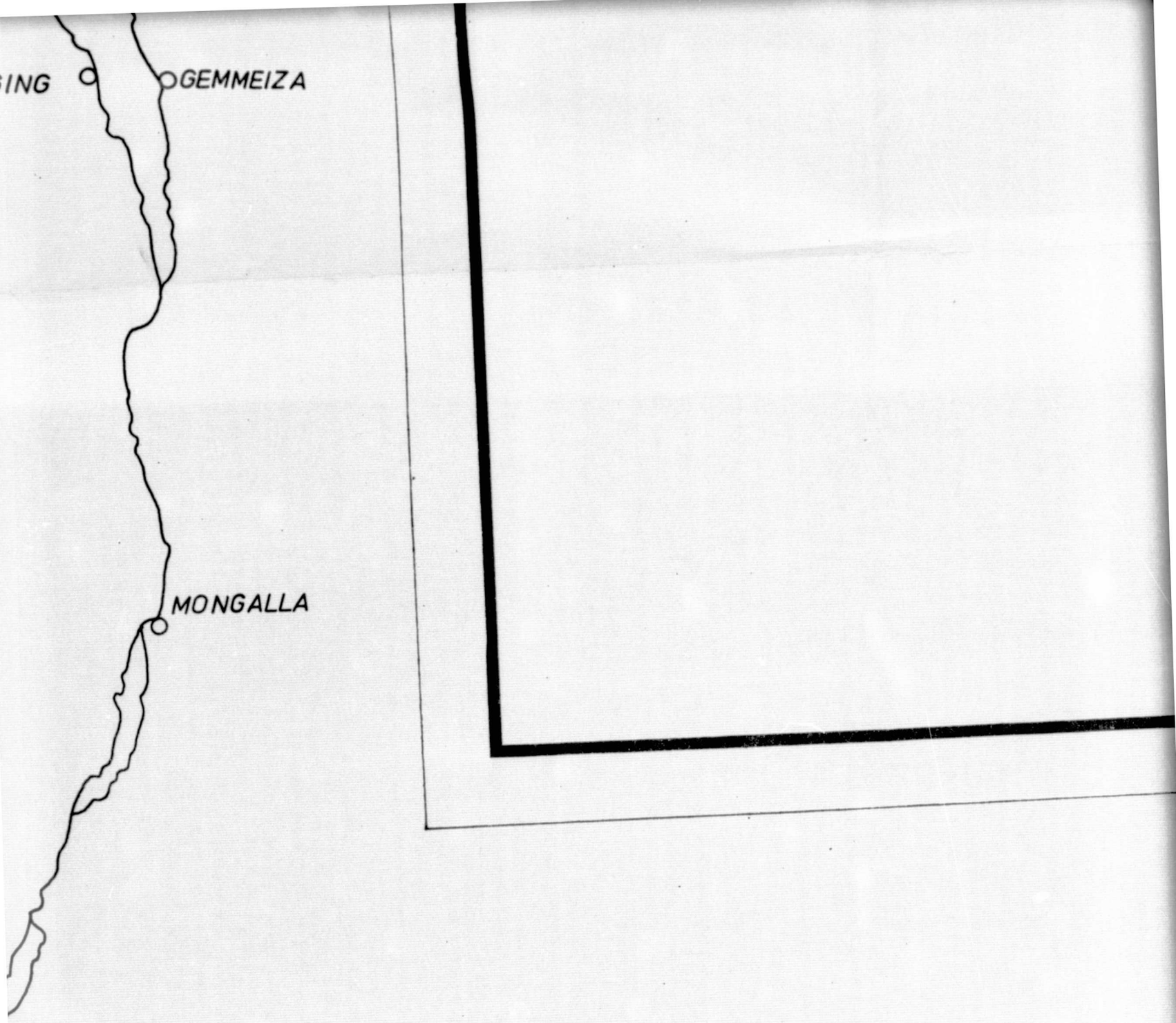
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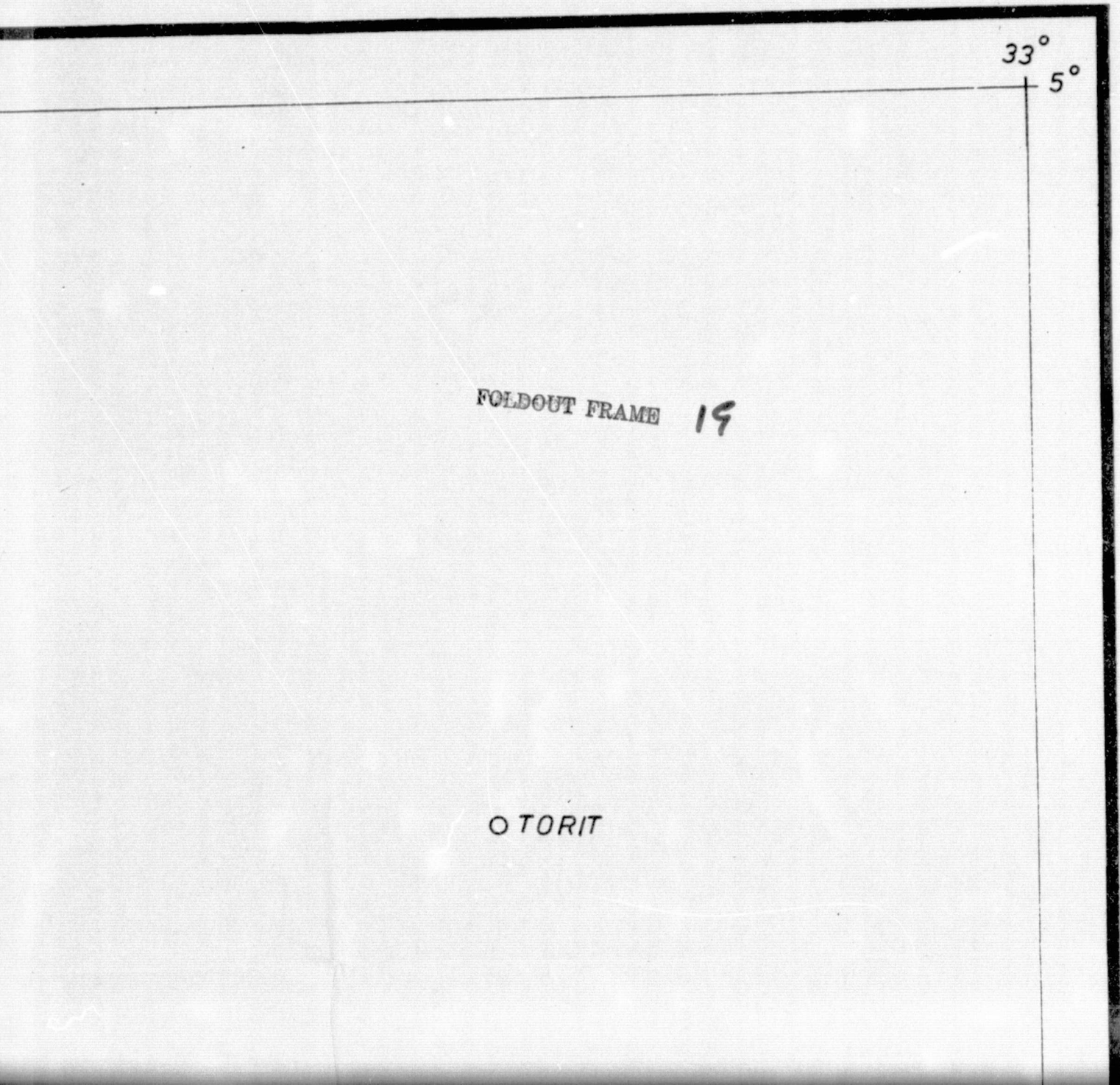
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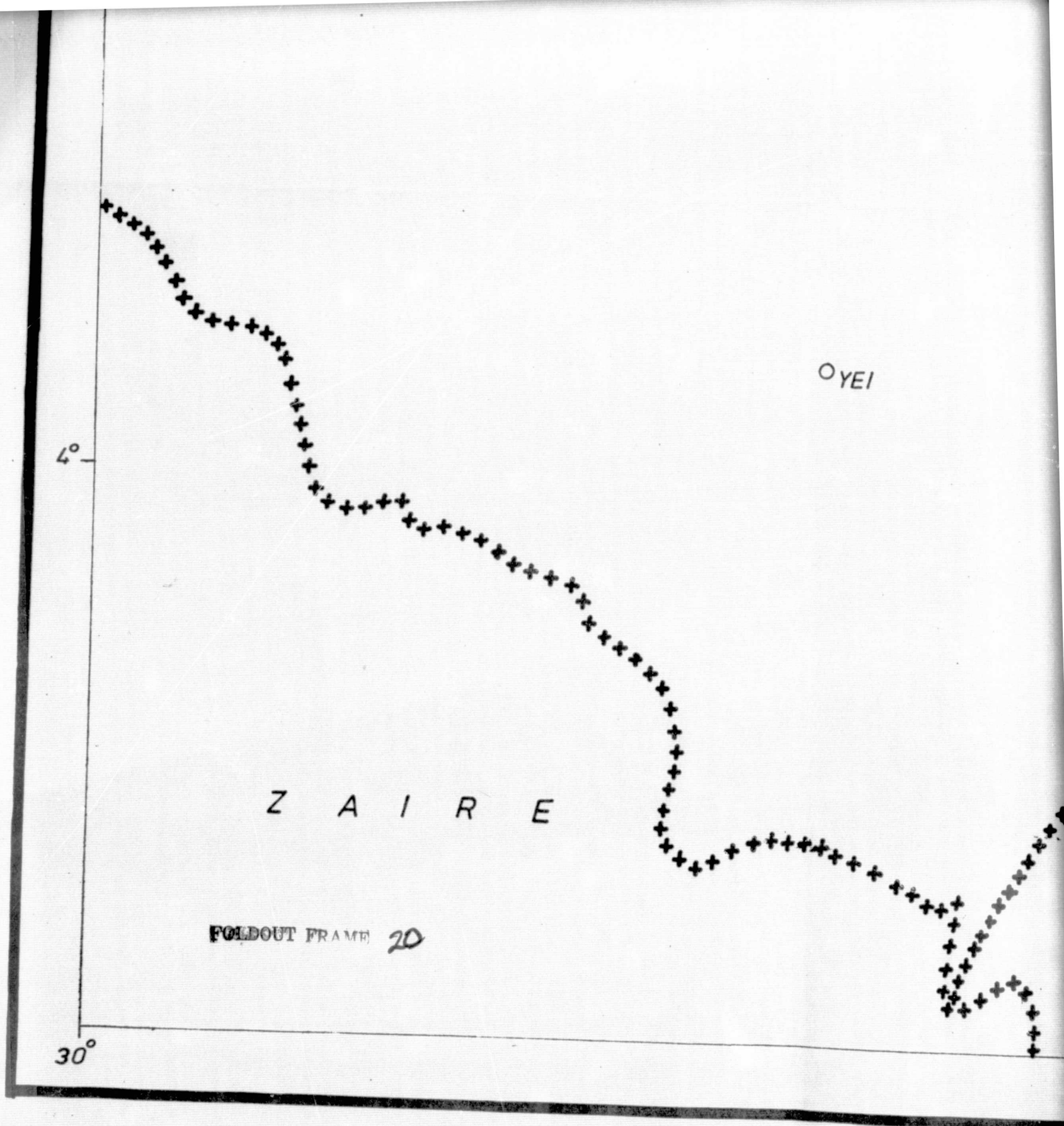
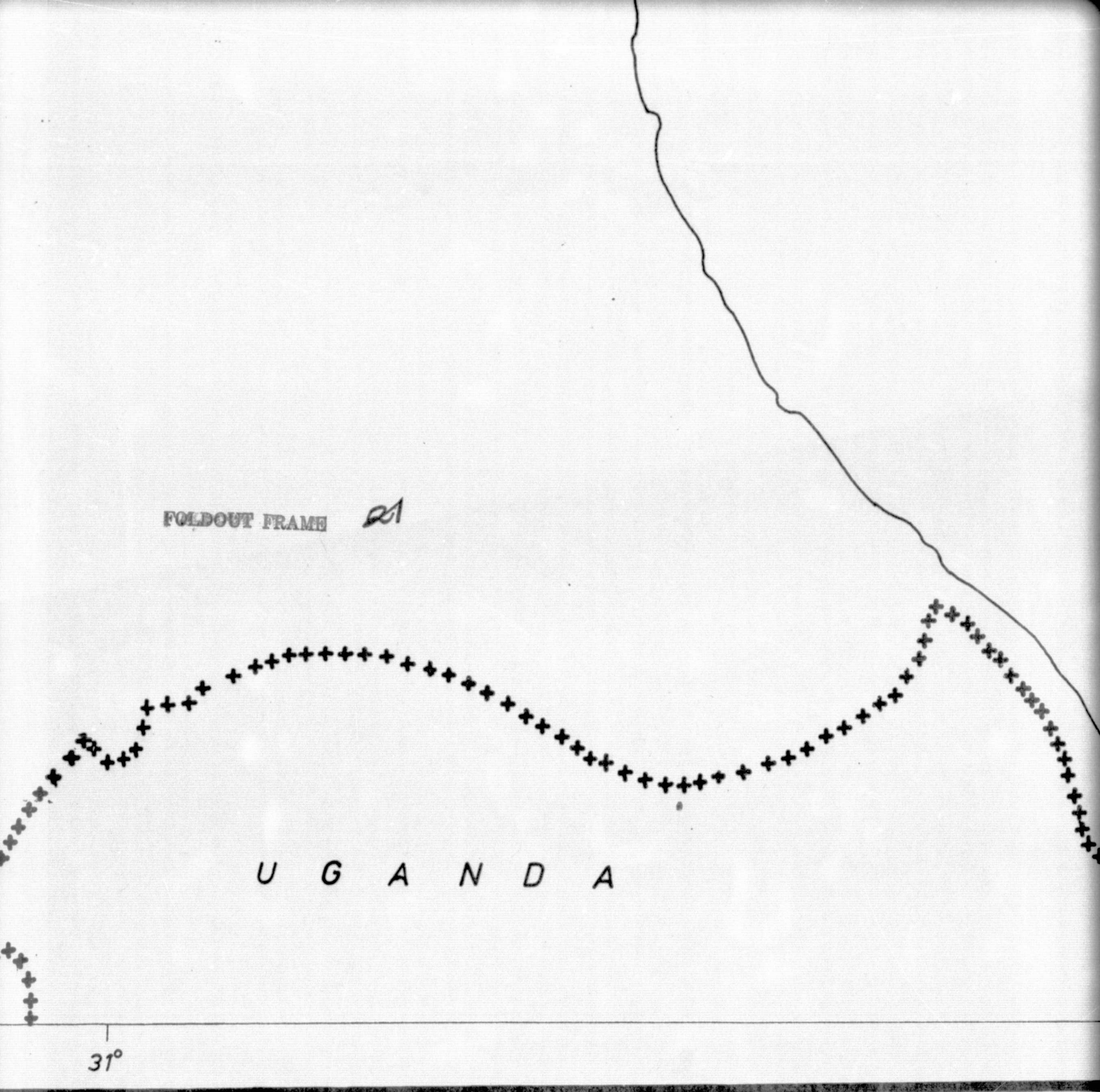
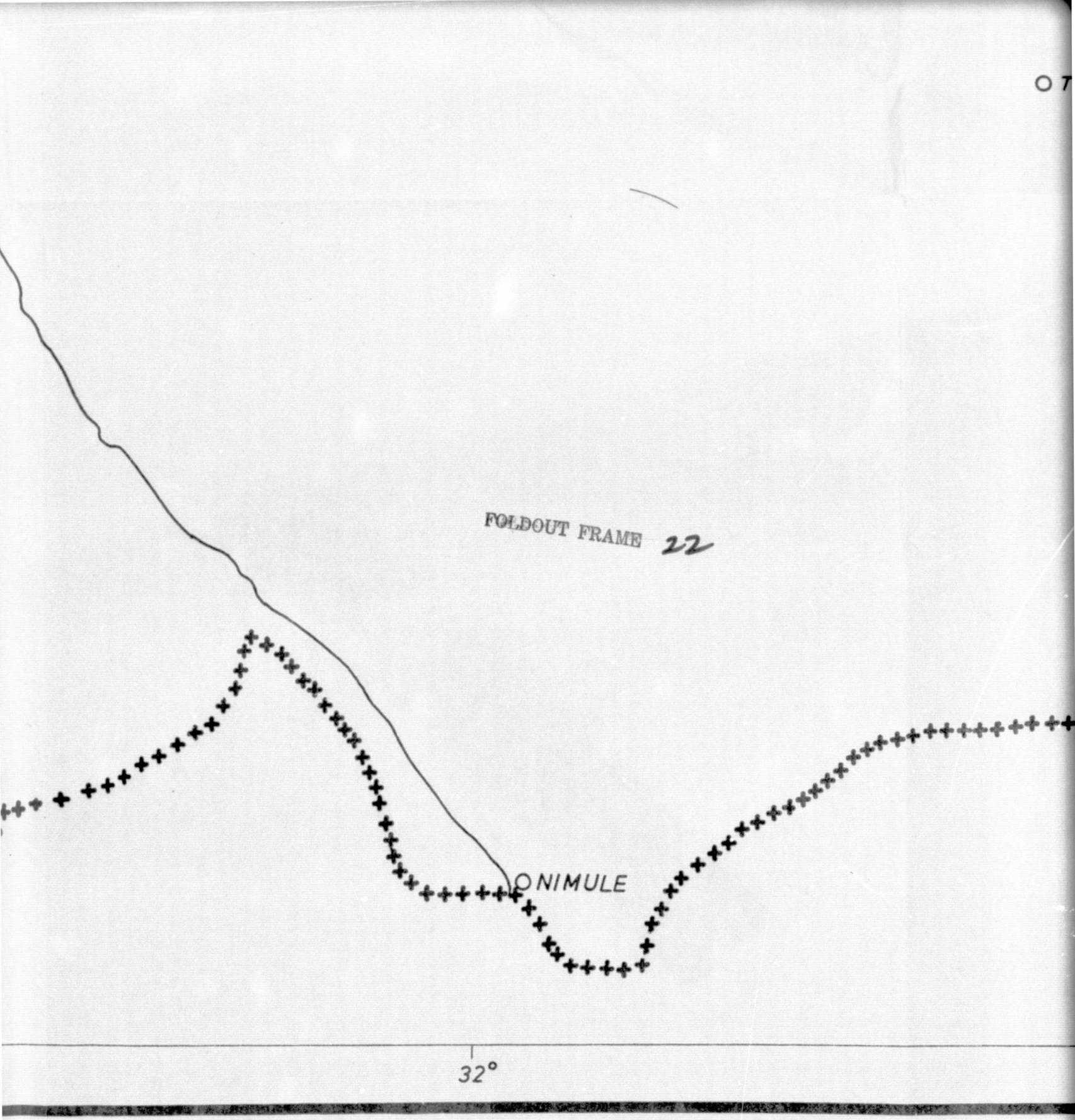


FIG. 8. ISO_ SAL



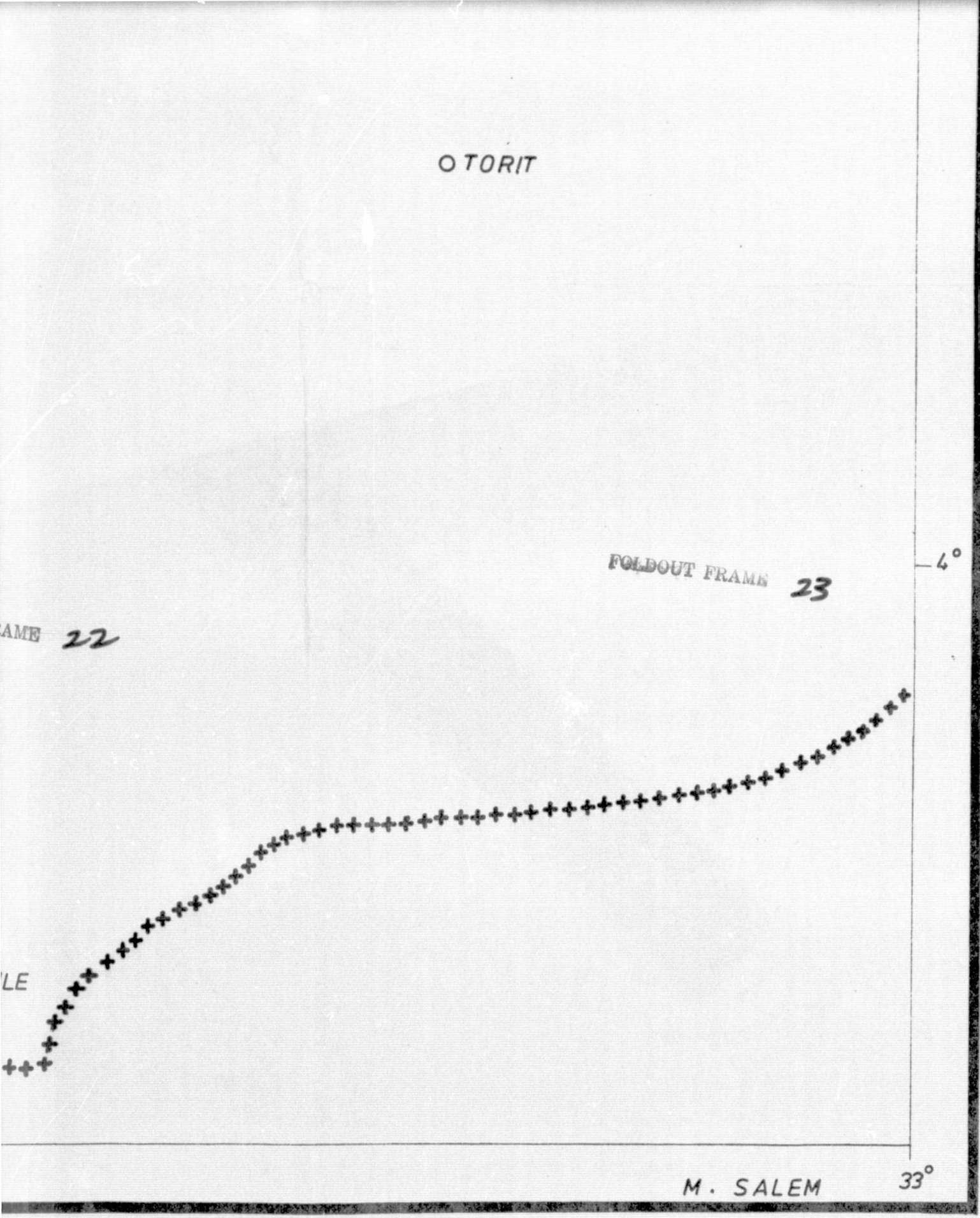
SALINITY CONTOUR MAP OF JONGLEI CA

SOUTHERN SUDAN



OF JONGLEI CANAL AREA,

DAN

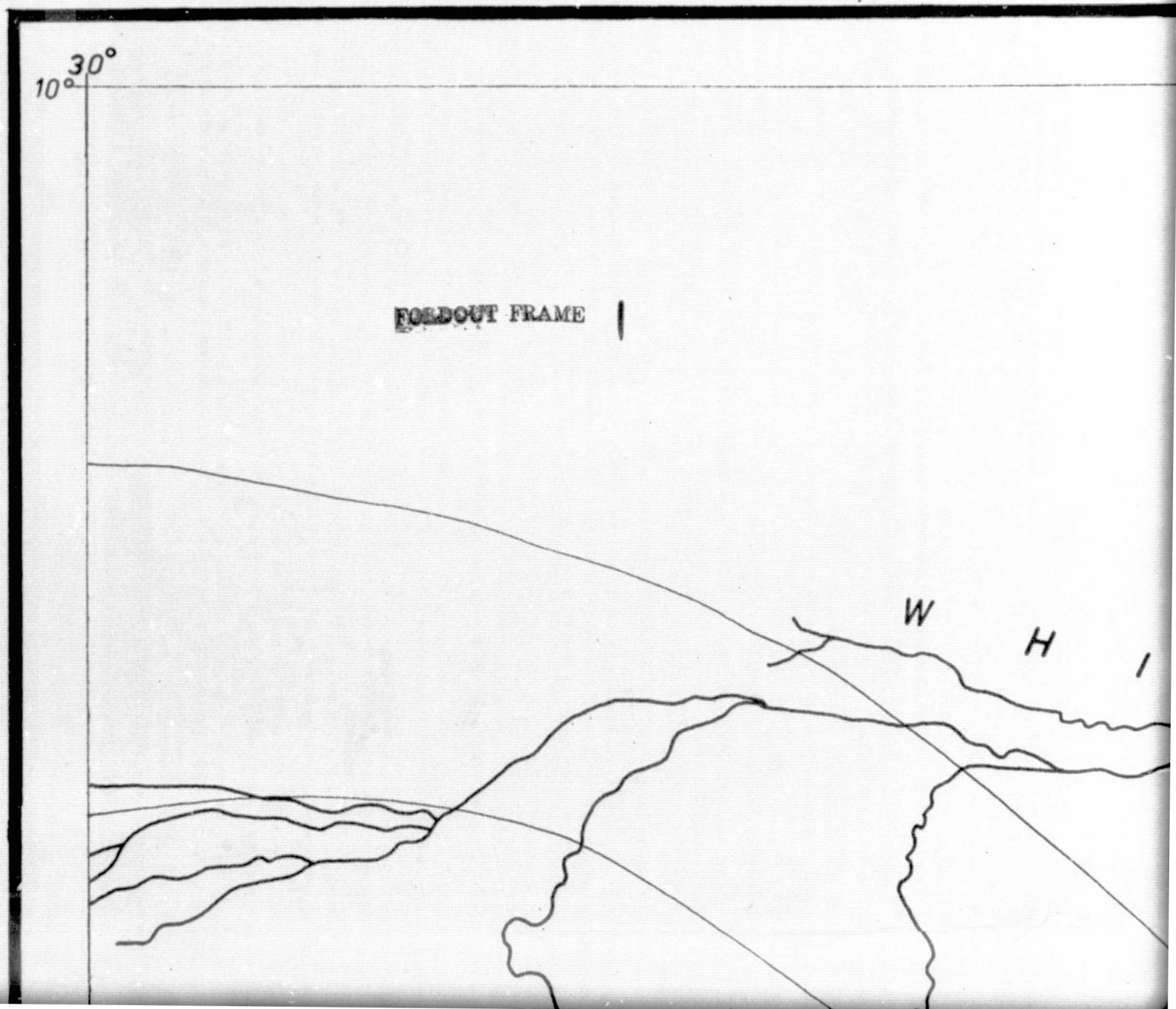


REA,

REMOTE SENSING CENTER

ACADEMY OF SCIENTIFIC RESEARCH AND TECH

CAIRO - EGYPT



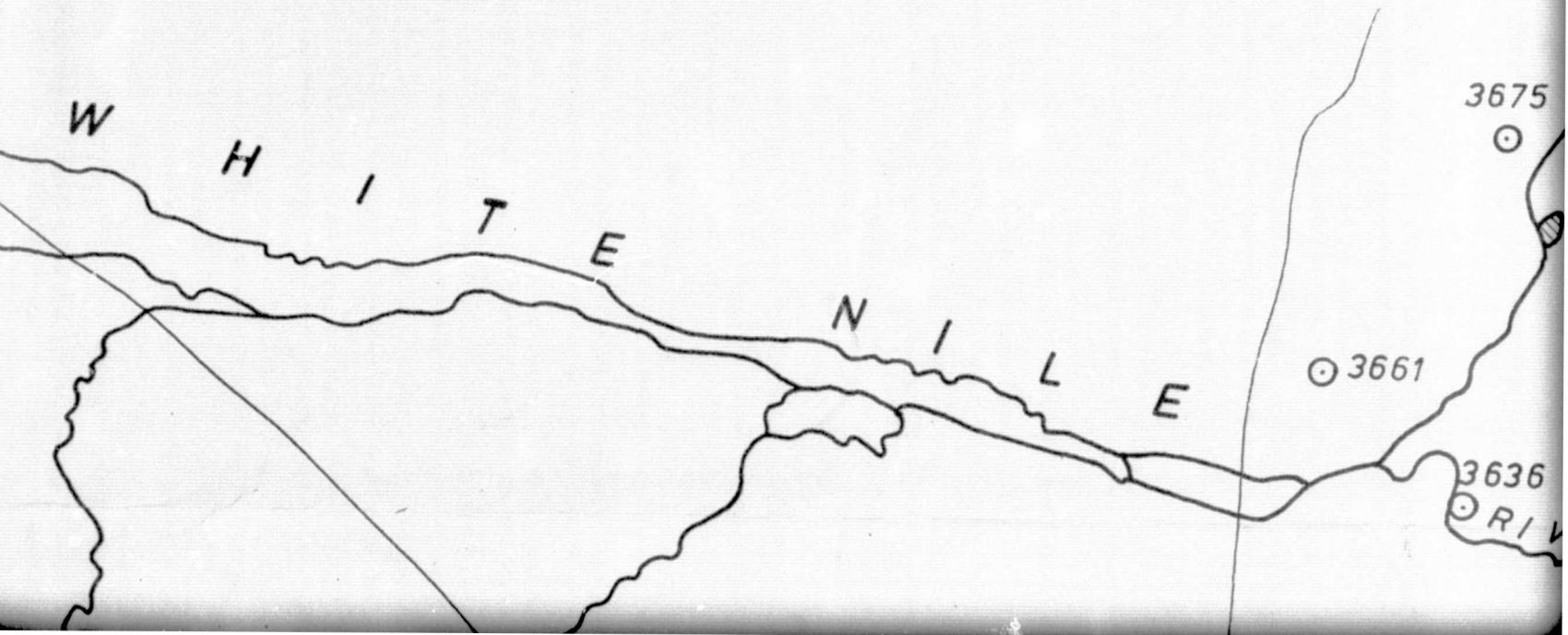
G CENTER

RCH AND TECHNOLOGY

SYPT

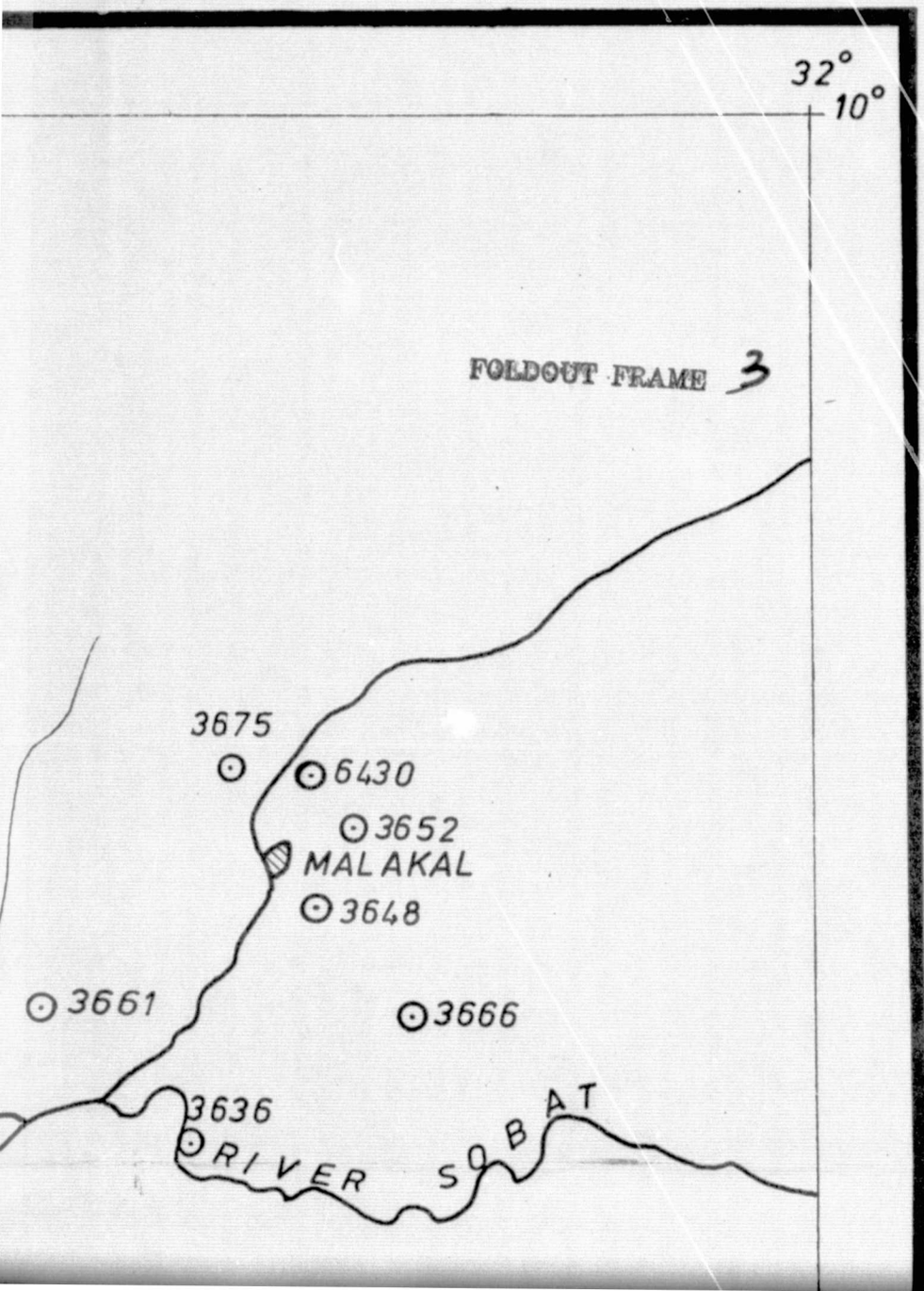
31°

FOLDOUT FRAME 2



MINISTRY OF IRRIGATION
ARAB REPUBLIC OF EGYPT

THE PERM
COMMISS



RY OF IRRIGATION,
REPUBLIC OF EGYPT

MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS

FOLDOUT FRAME 4

9°

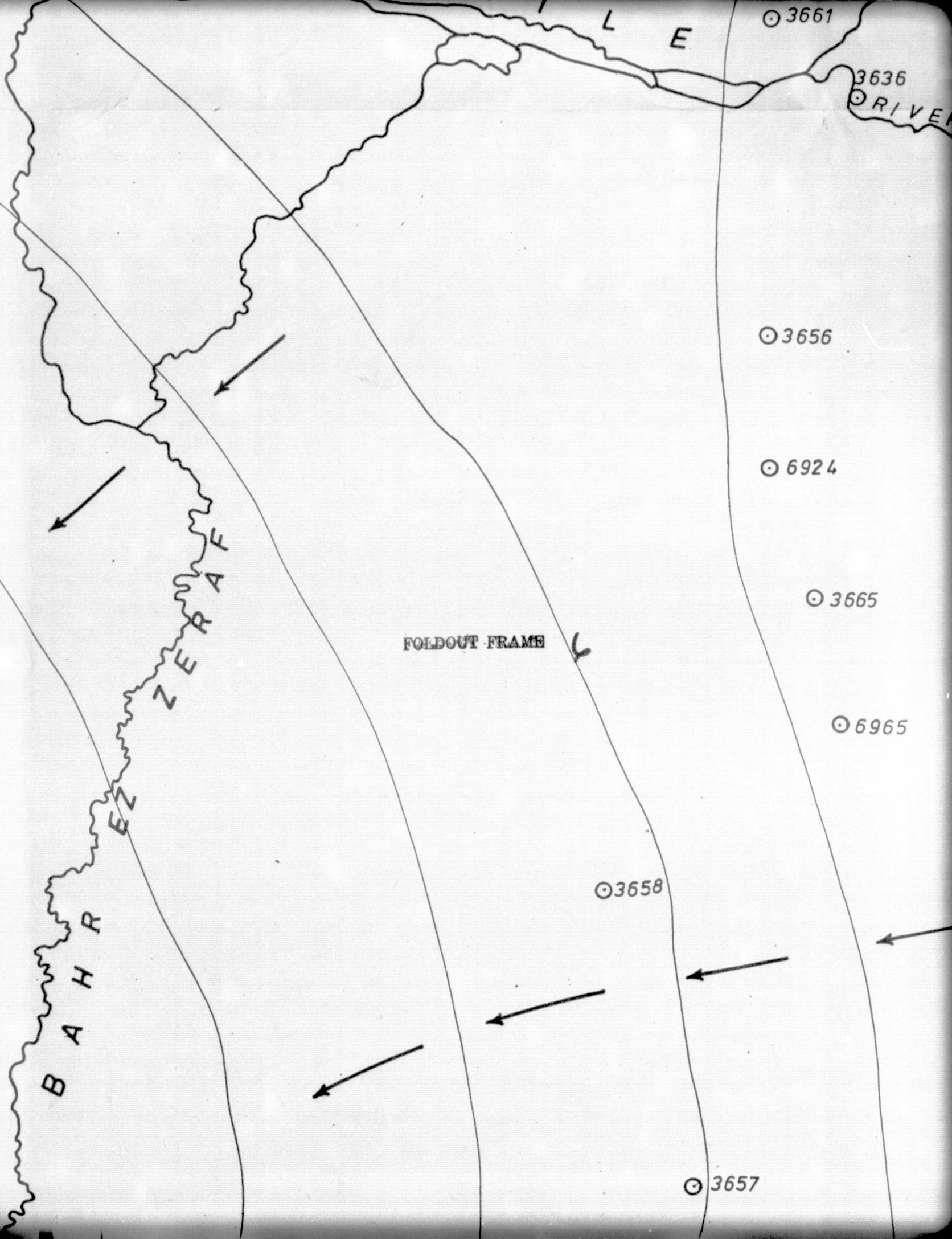
BAHR EL JEBEL

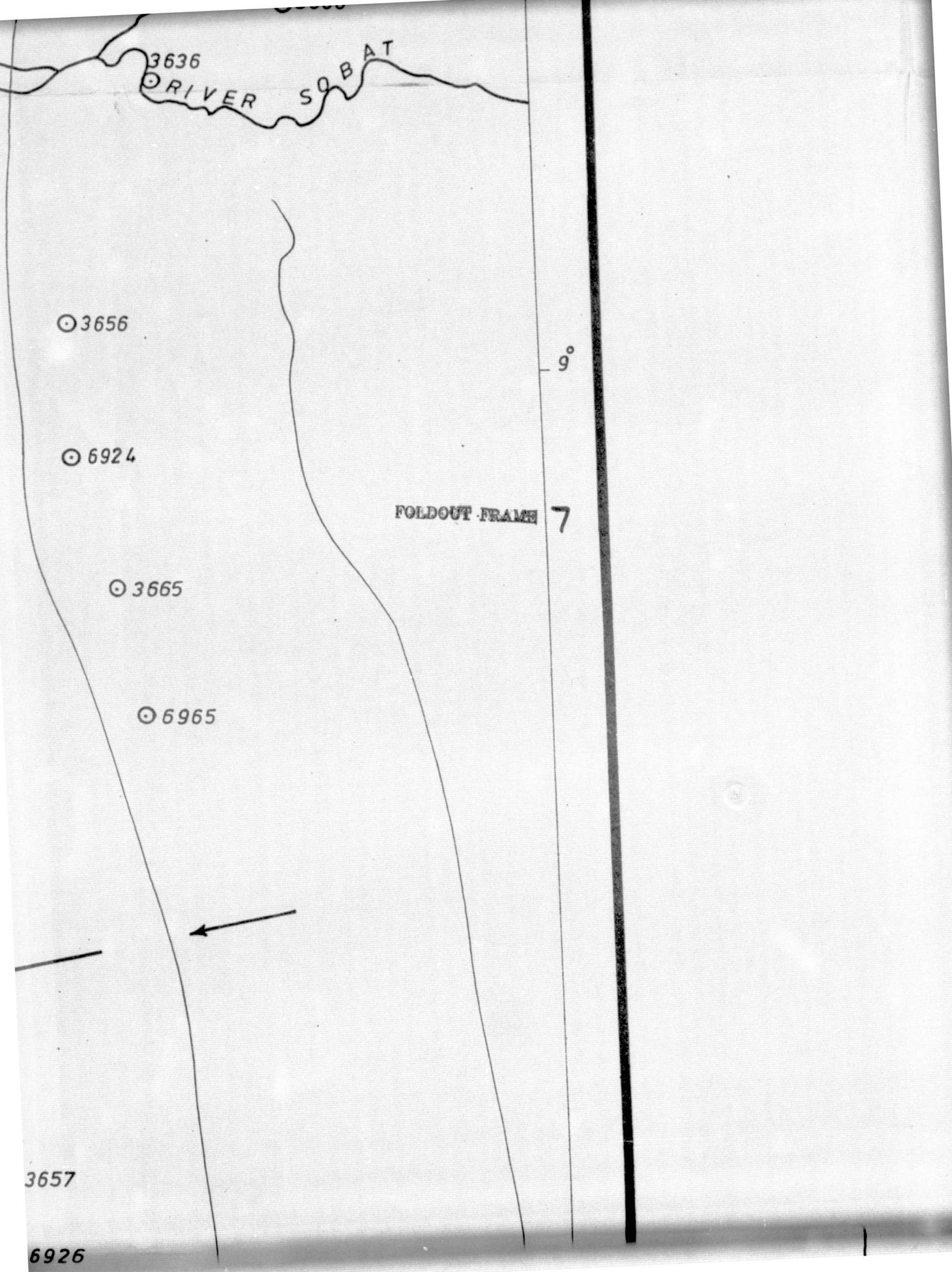
FOLDOUT FRAME

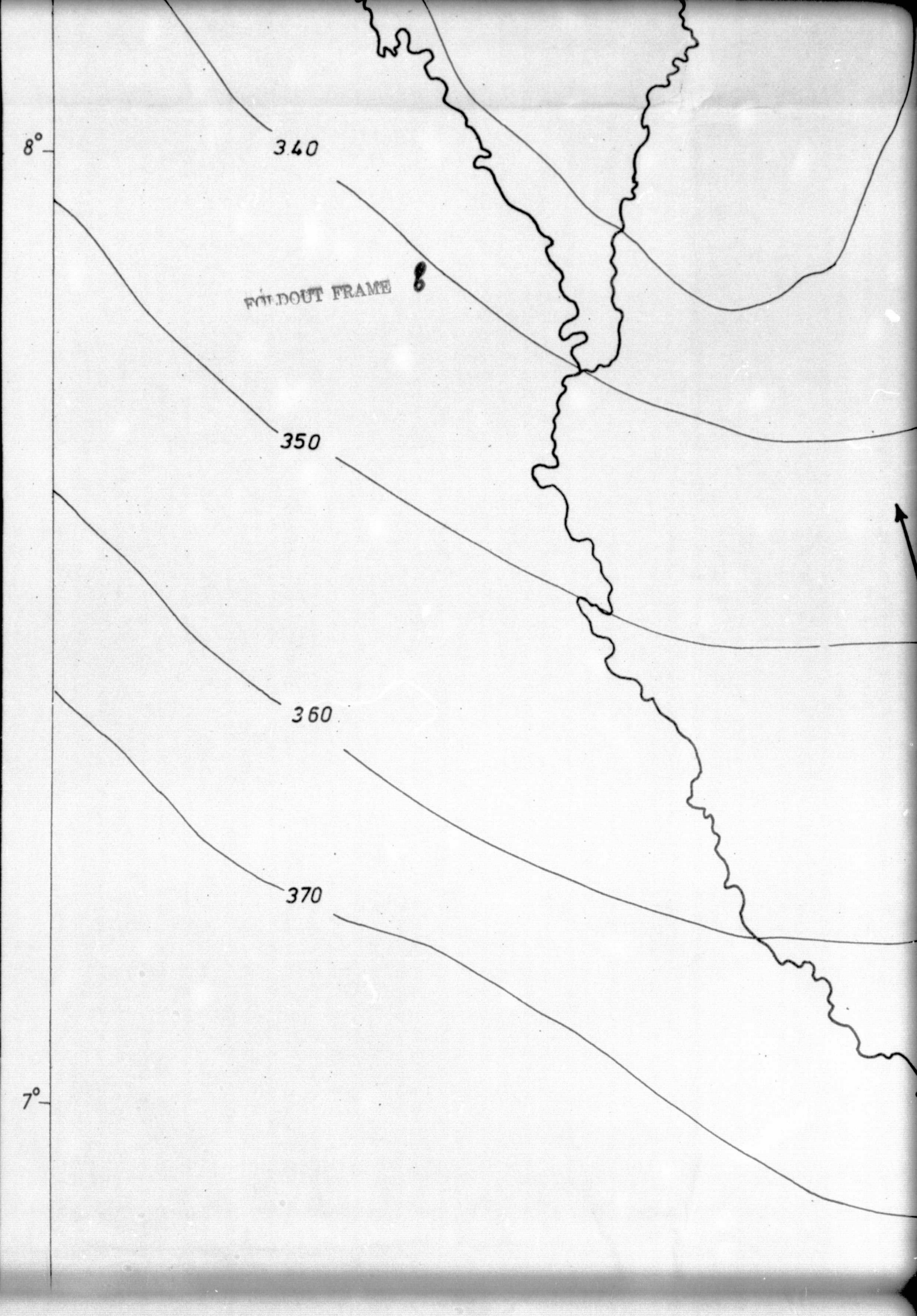
320

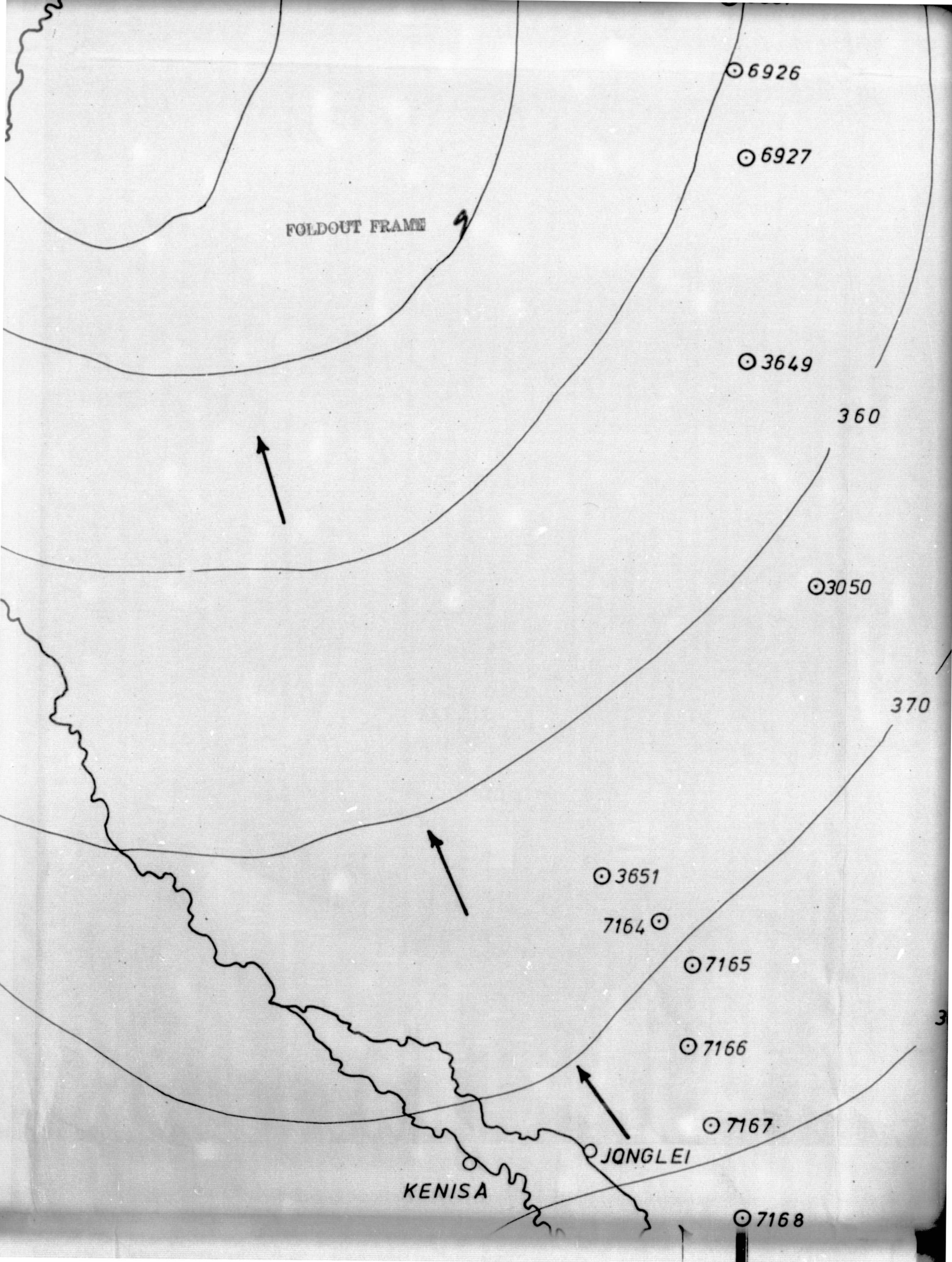
330

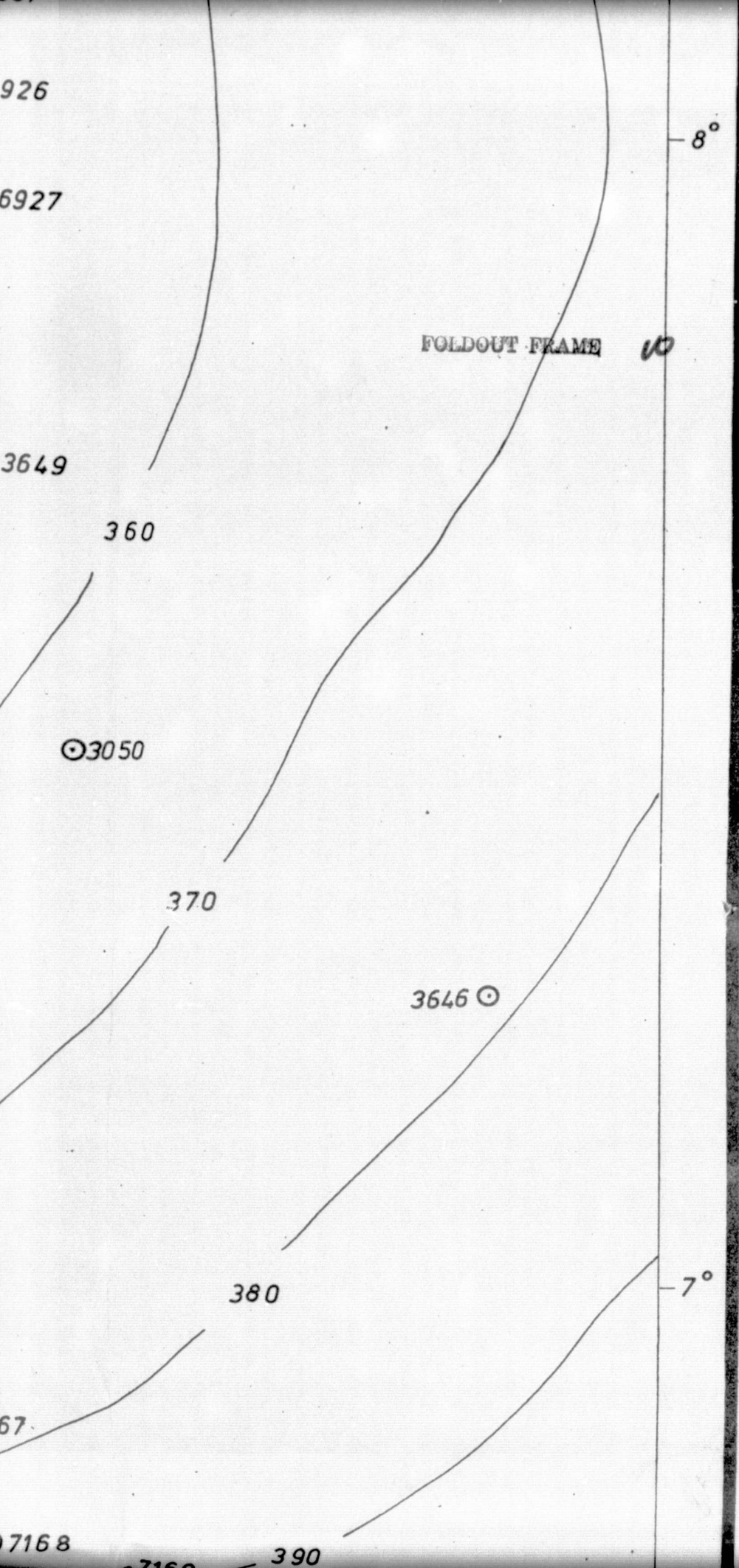
BAHR EZ ZERAF


L E
3661
3636
RIVE
3656
6924
3665
FOLDOUT FRAME
6965
3658
3657
BAHR EZ ZERAF


3636
RIVER SOBAT
3656
9°
6924
FOLDOUT FRAME 7
3665
6965
3657
6926


8°
340
FOLDOUT FRAME
350
360
370
7°


6926
6927
FOLDOUT FRAME
3649
360
3050
370
3651
7164
7165
7166
7167
JONGLEI
KENISA
7168



5 0 5

3657 WELL No.

FOLDOUT FRAME 11

5 0 5 10 15 20 25 30 35 km

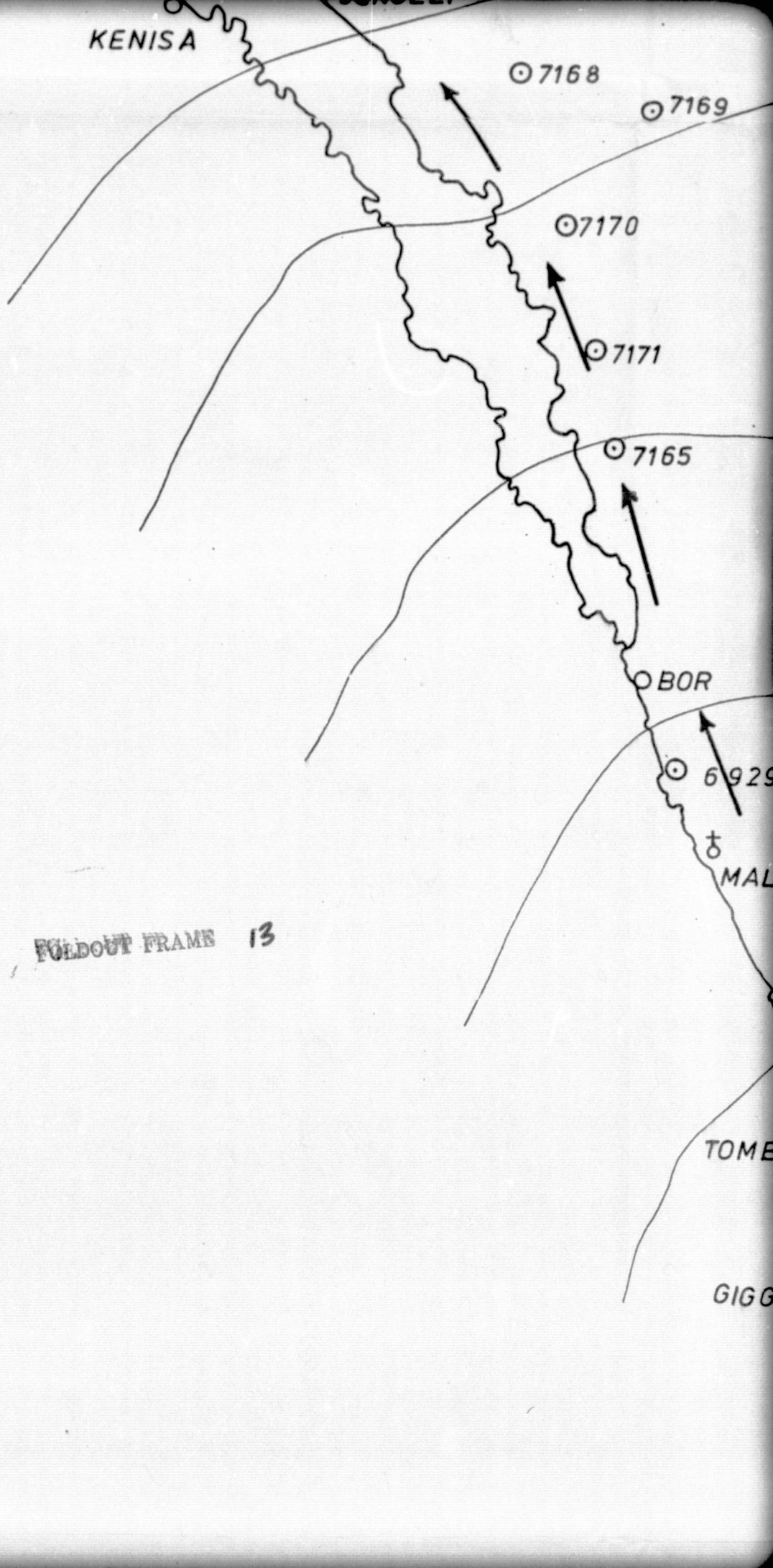
LEGEND

3657
⊙ WELL No.

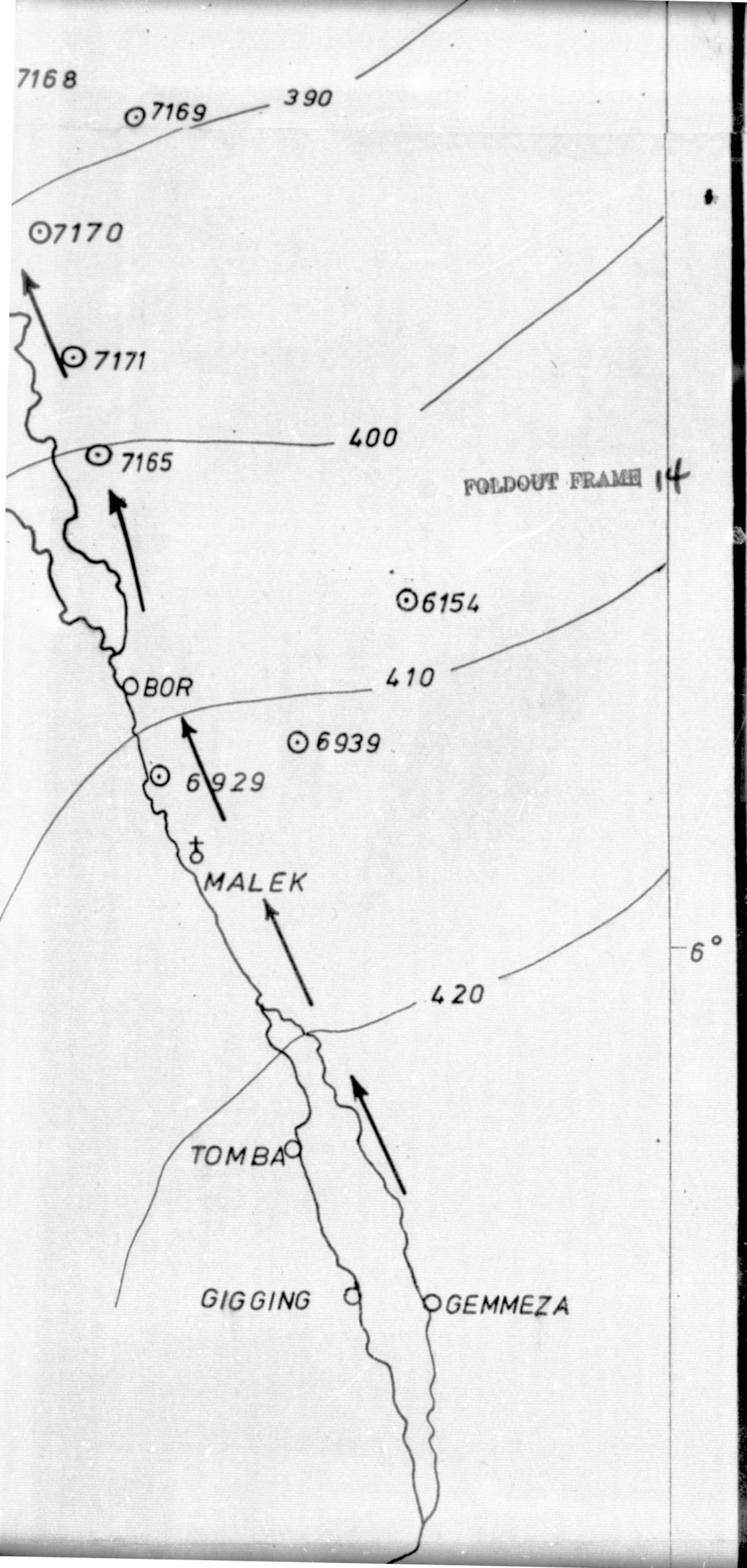
FOLDOUT FRAME 12

6°

E-3



FOLDOUT FRAME 13



FOLDOUT FRAME 14

WELL No.

360 WATER LEVEL

DIRECTION OF

CITIES AND T

SETTLEMENTS

MISSIONARIES

3657 ⊙ WELL No.

350 WATER LEVEL CONTOUR IN m

 DIRECTION OF GROUNDWATER FLOW

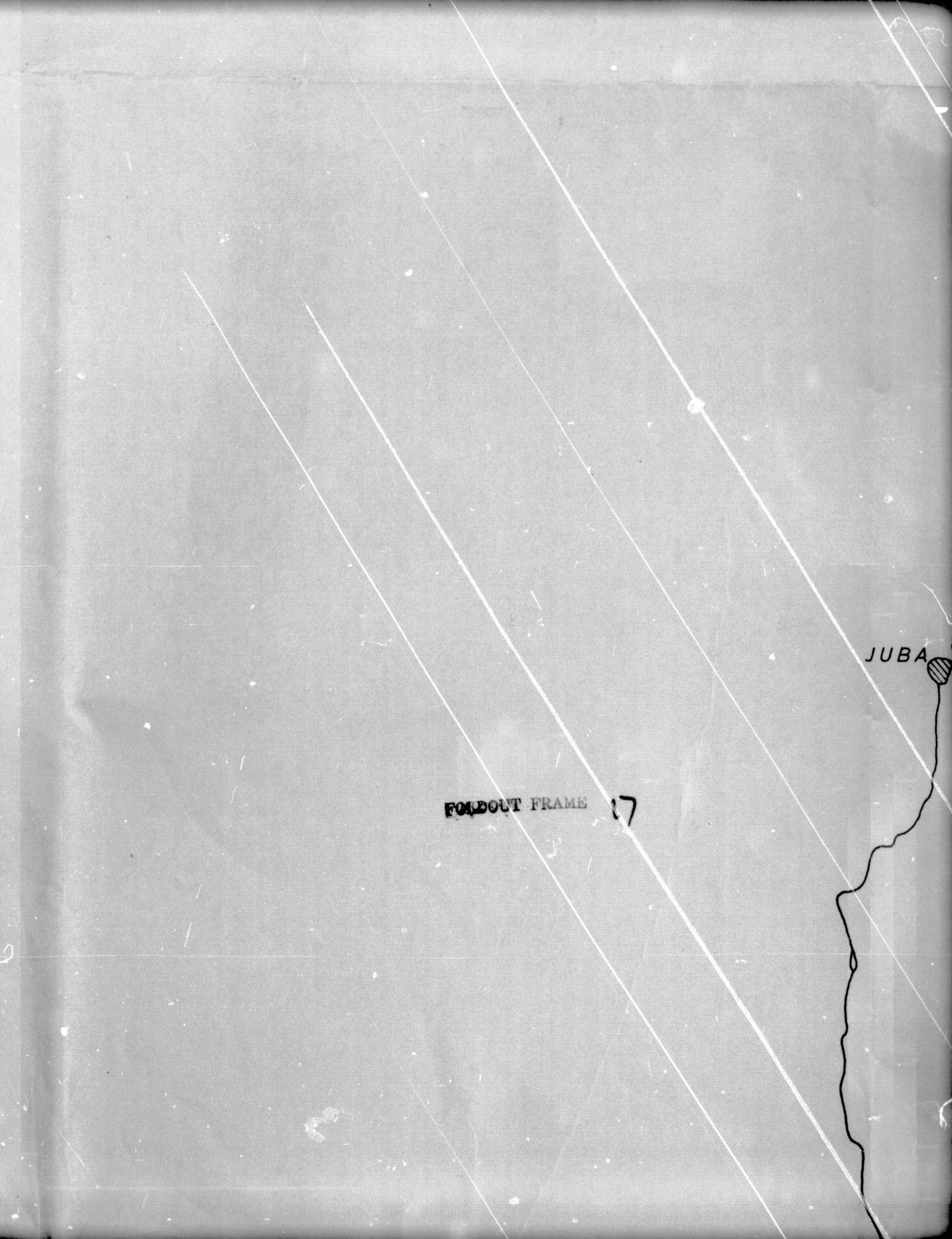
 CITIES AND TOWNS

FOLDOUT FRAME 15

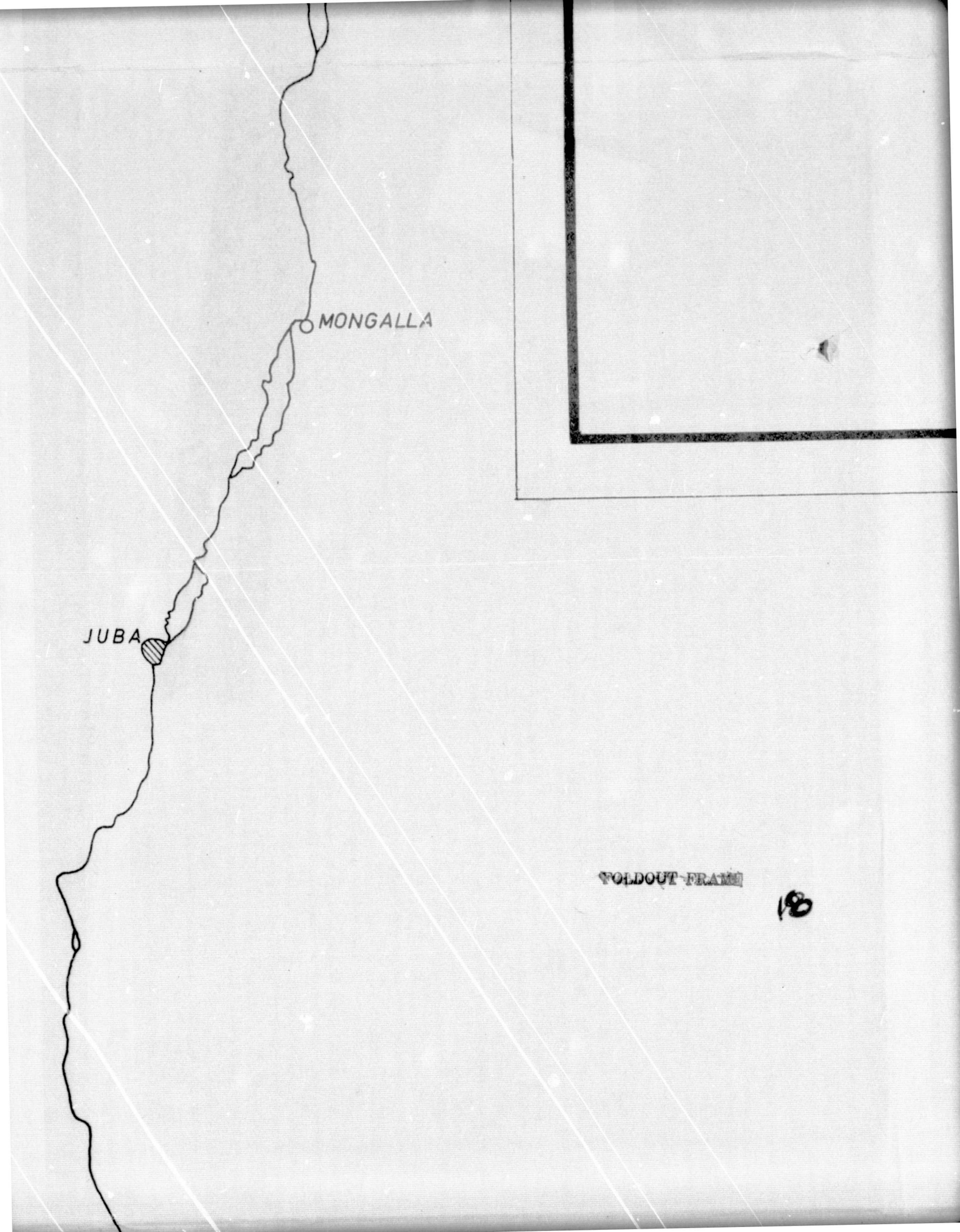
○ SETTLEMENTS AND SMALL TOWNS

† MISSIONARIES

FOLDOUT FRAME 14



FOLDOUT FRAME 17



FOLDOUT FRAME

33°

5°

FOLDOUT FRAME 19

FRAME

18

O TORIT

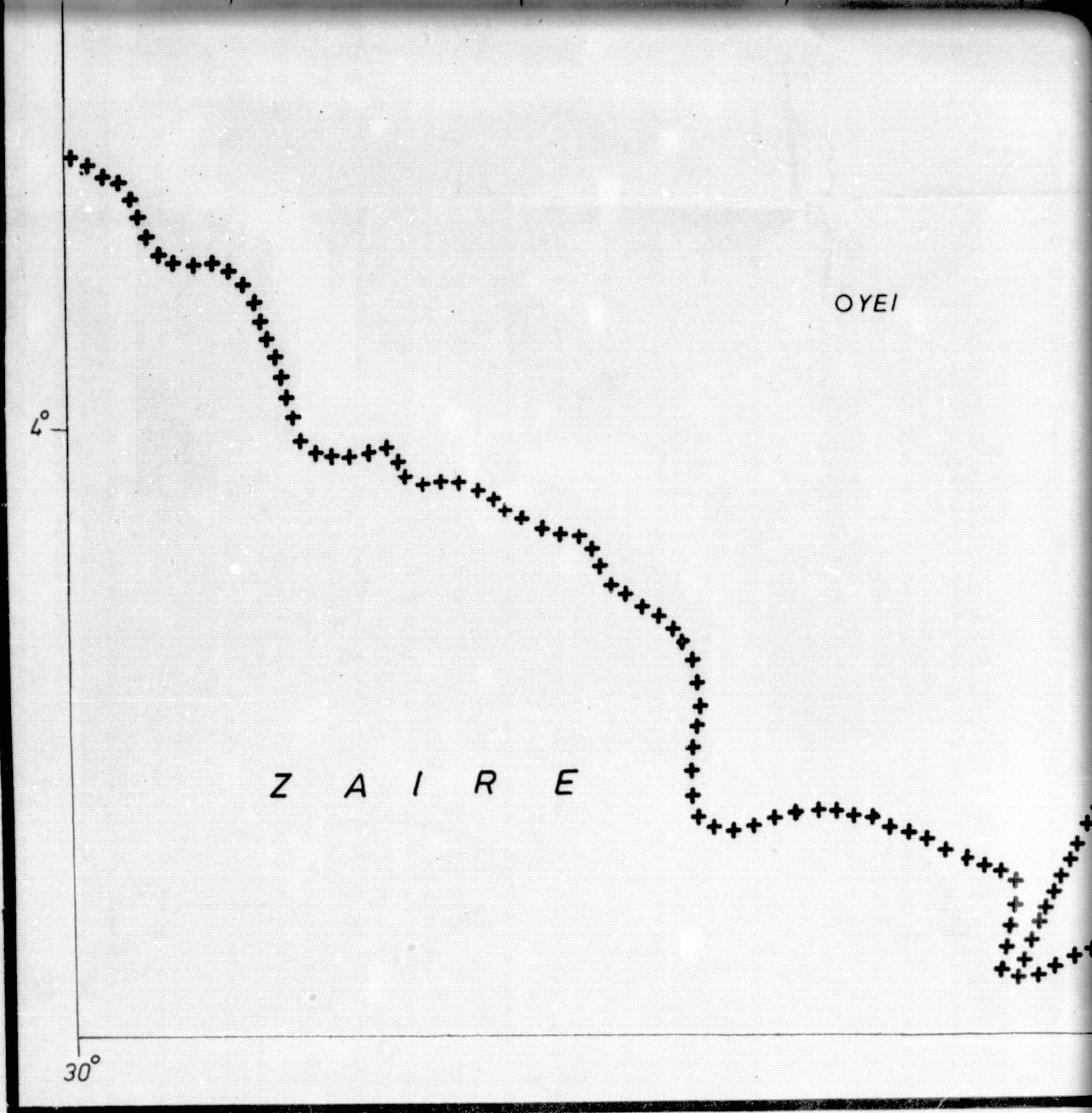
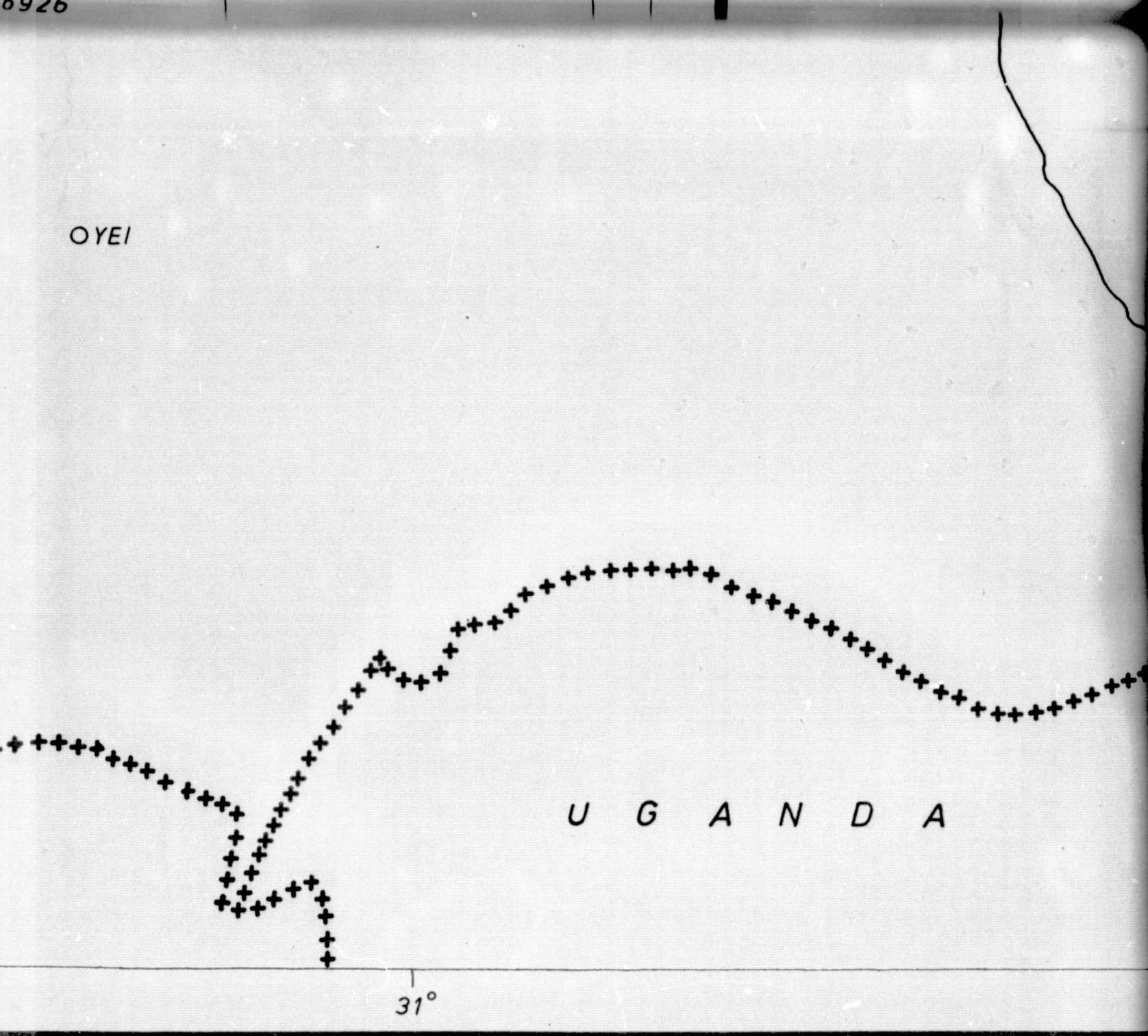


FIG.7. WATE

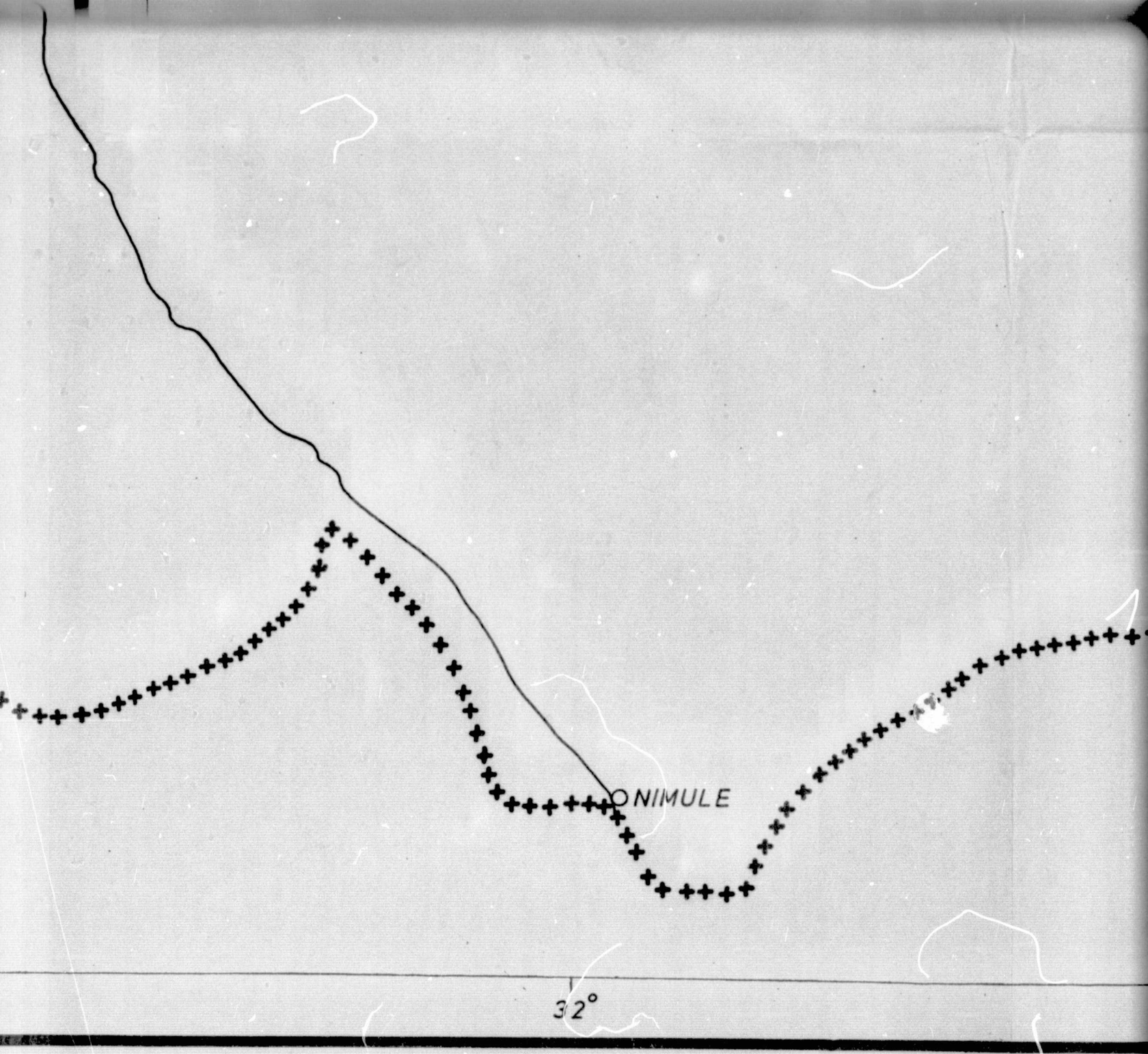
FOLDOUT FRAME 10

6926



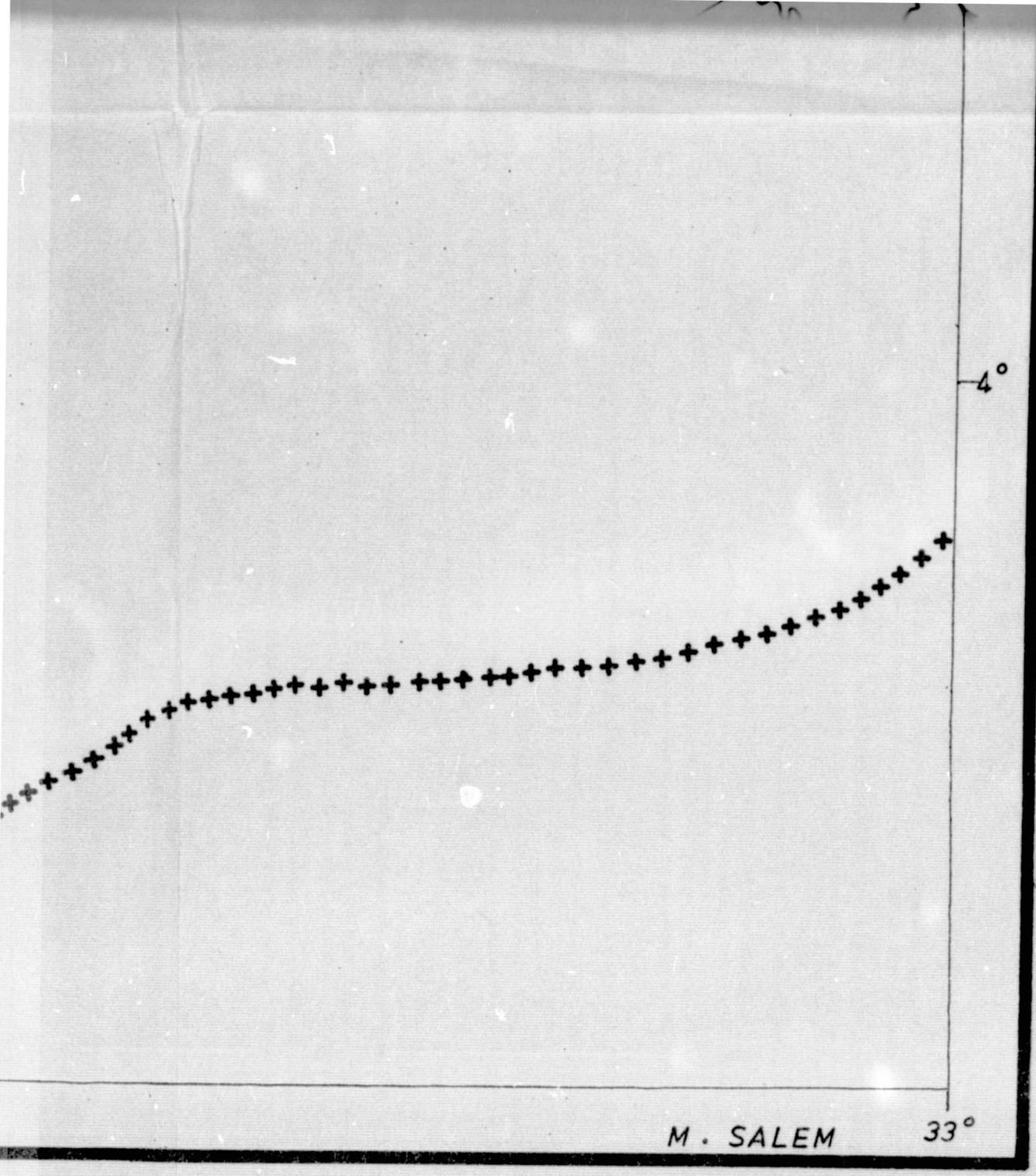
IG.7. WATER TABLE CONTOUR MAP OF SOUTHERN SUDAN.

FOLDOUT FRAME 21



MAP OF JONGLEI CANAL AREA,
SUDAN.

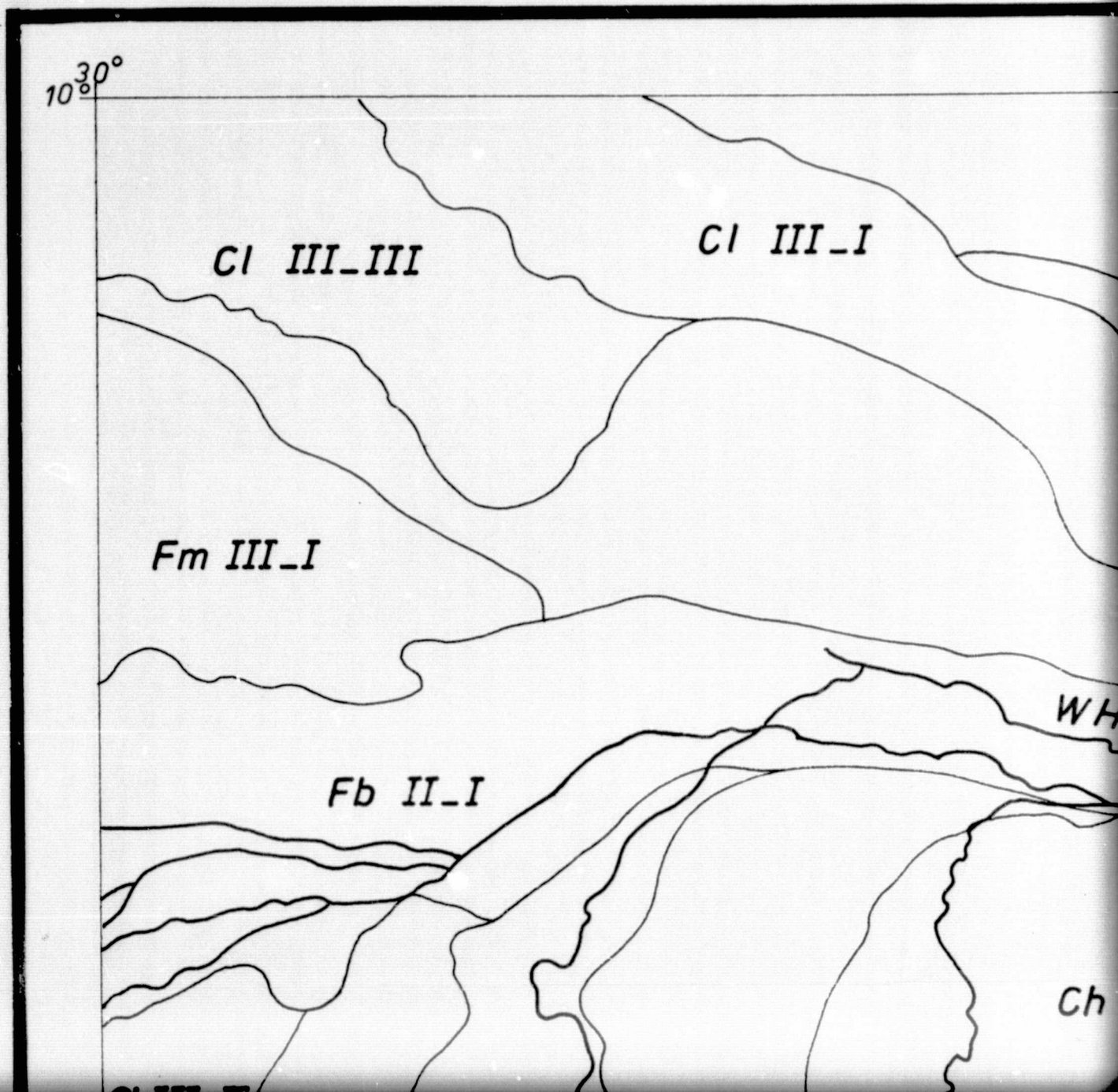
REPORT FRAME 22


4°
M . SALEM
33°

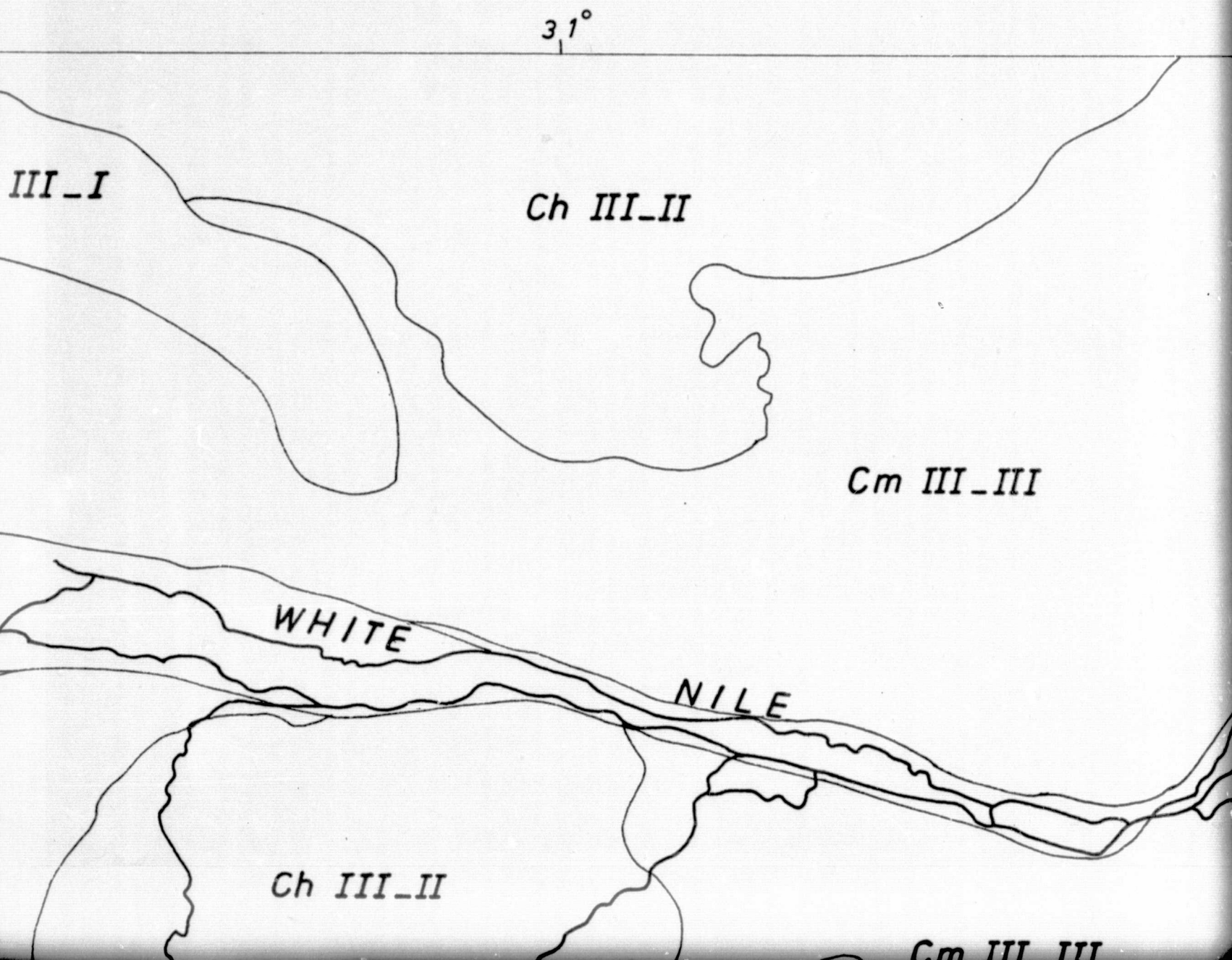
FOLDOUT FRAME 1

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ACADEMY OF SCIENTIFIC RESEARCH AND T



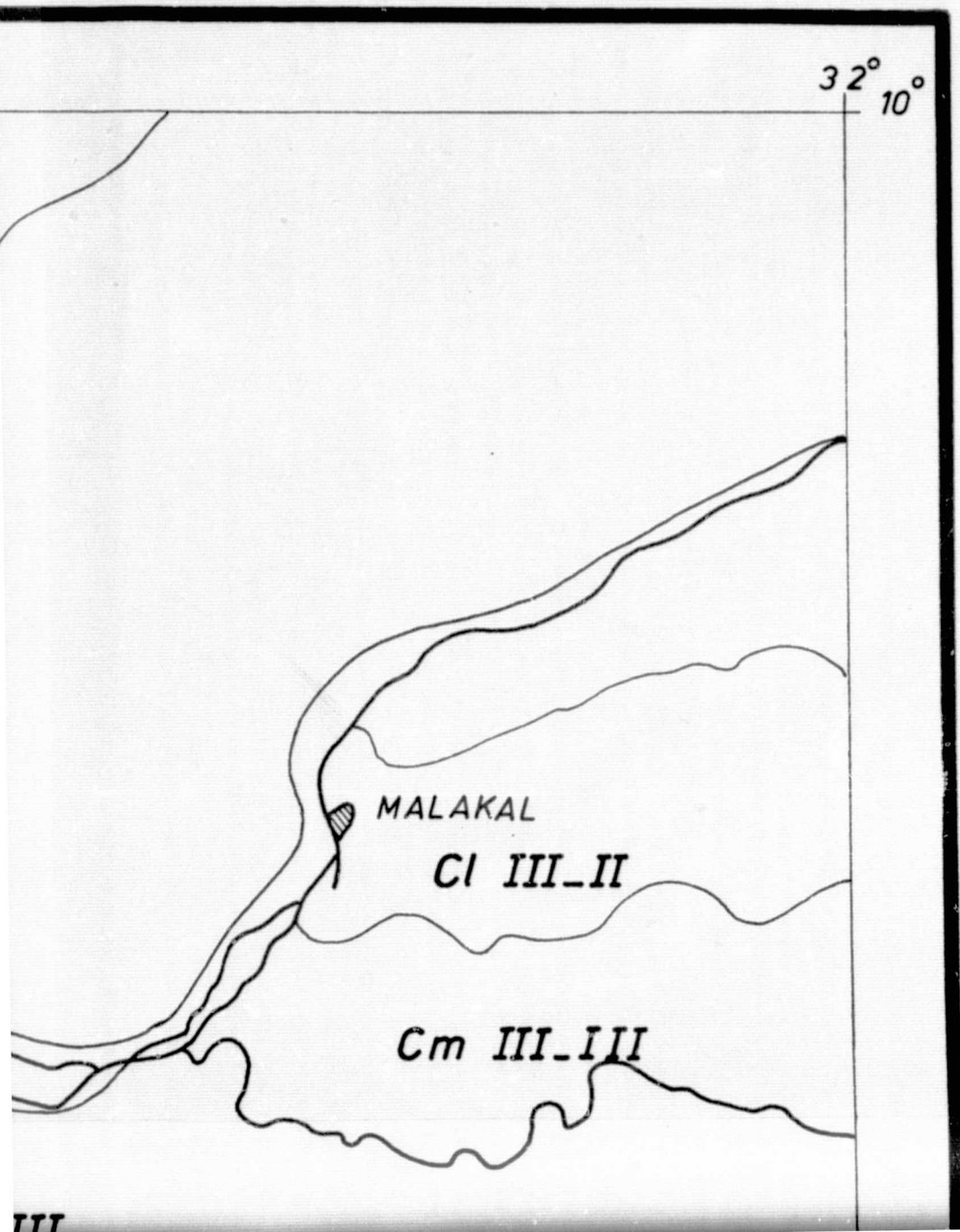
FOLDOUT FRAME 2



FOLDOUT FRAME 3

MINISTRY OF IRRIGATION
ARAB REPUBLIC OF EGYPT

THE PERM
COMMIS



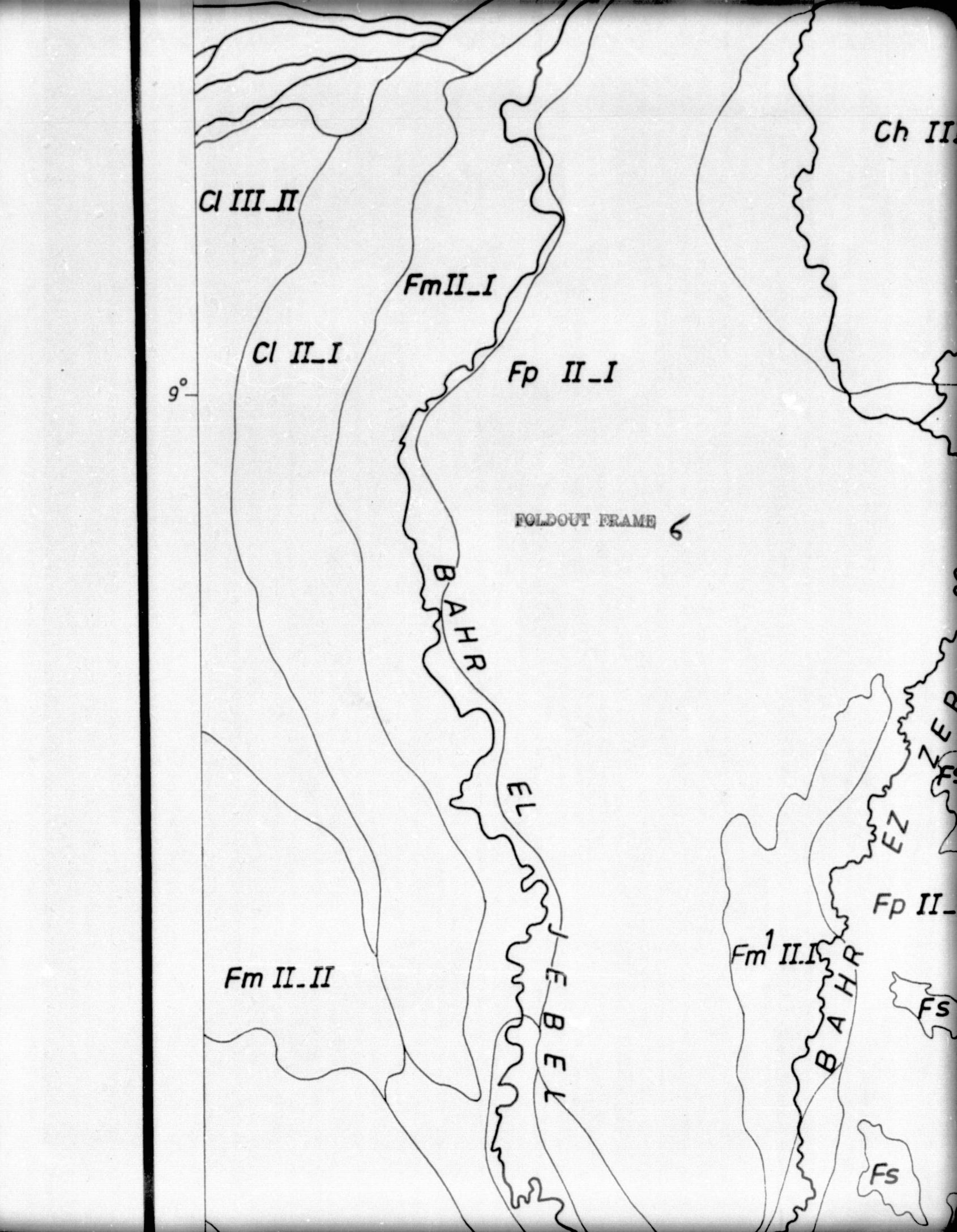
III

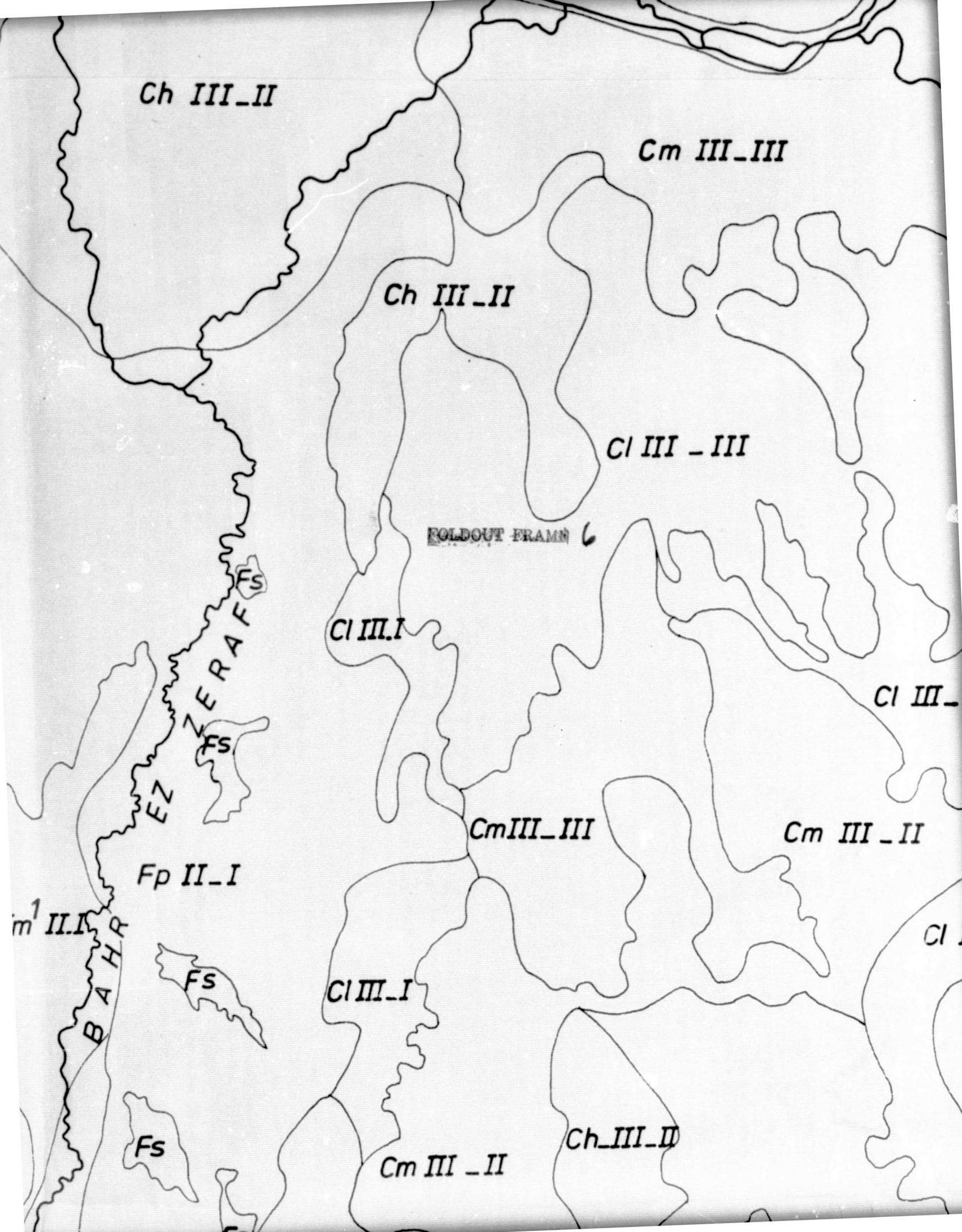
FOLDOUT FRAME 4

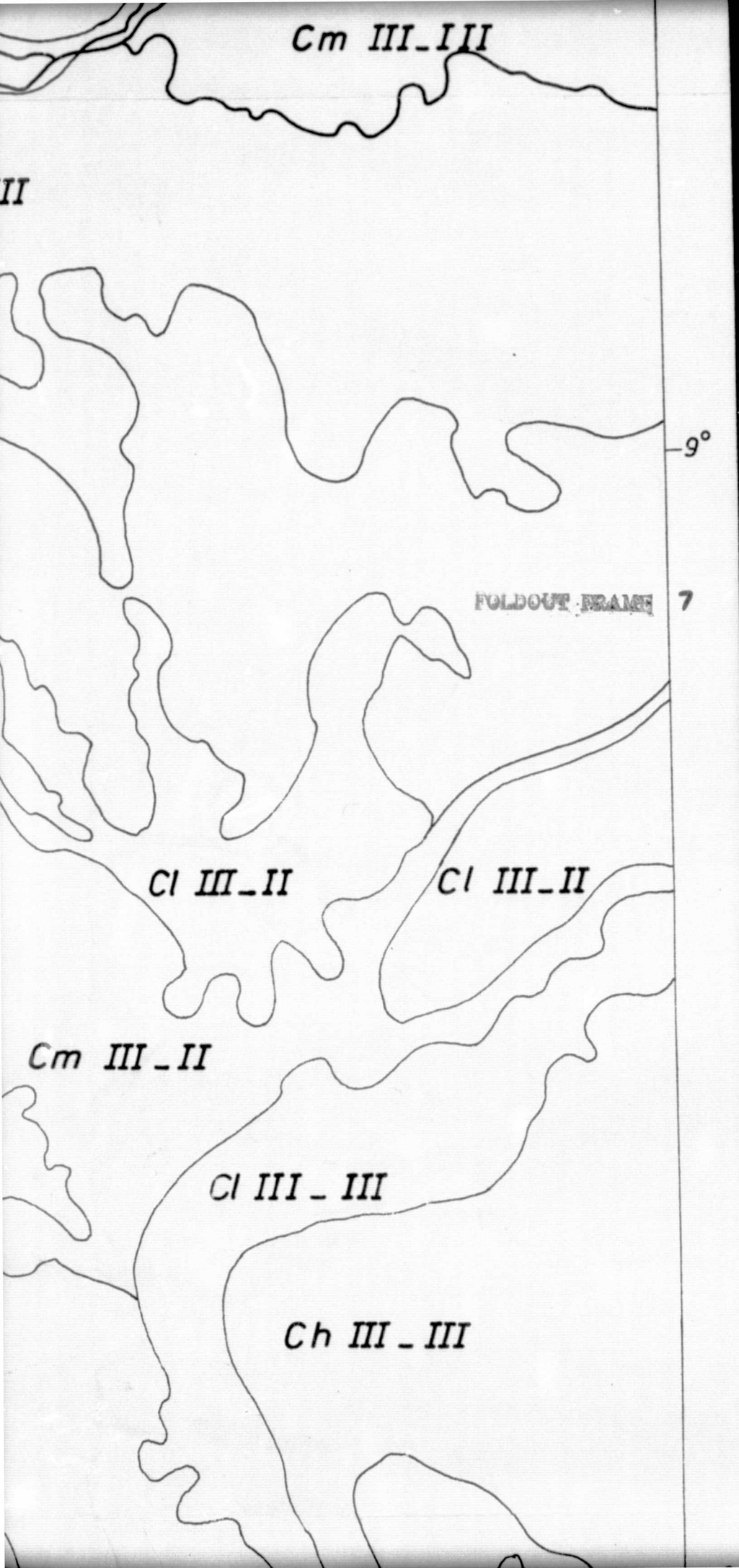
STRY OF IRRIGATION,
REPUBLIC OF EGYPT

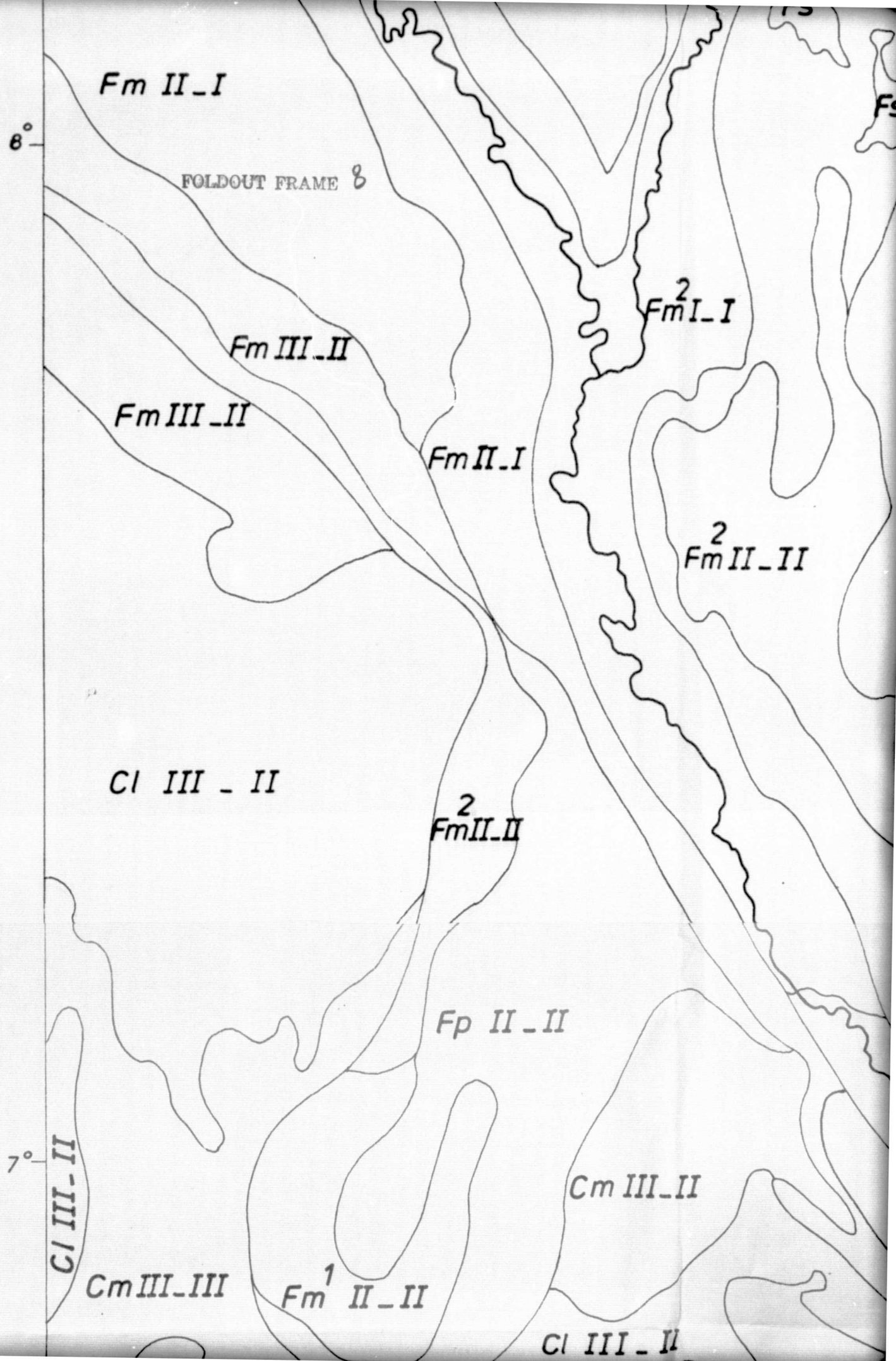
MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

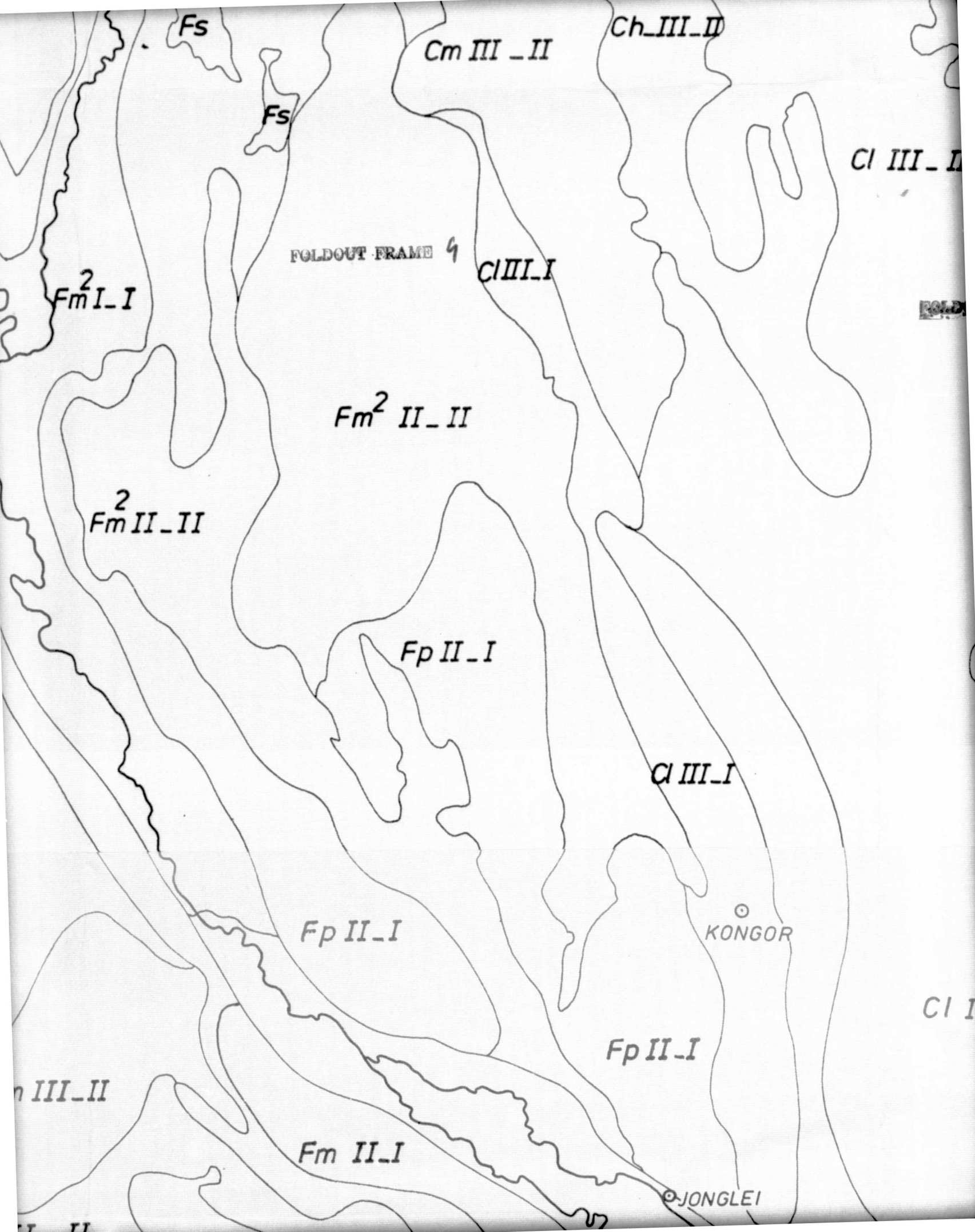
THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS

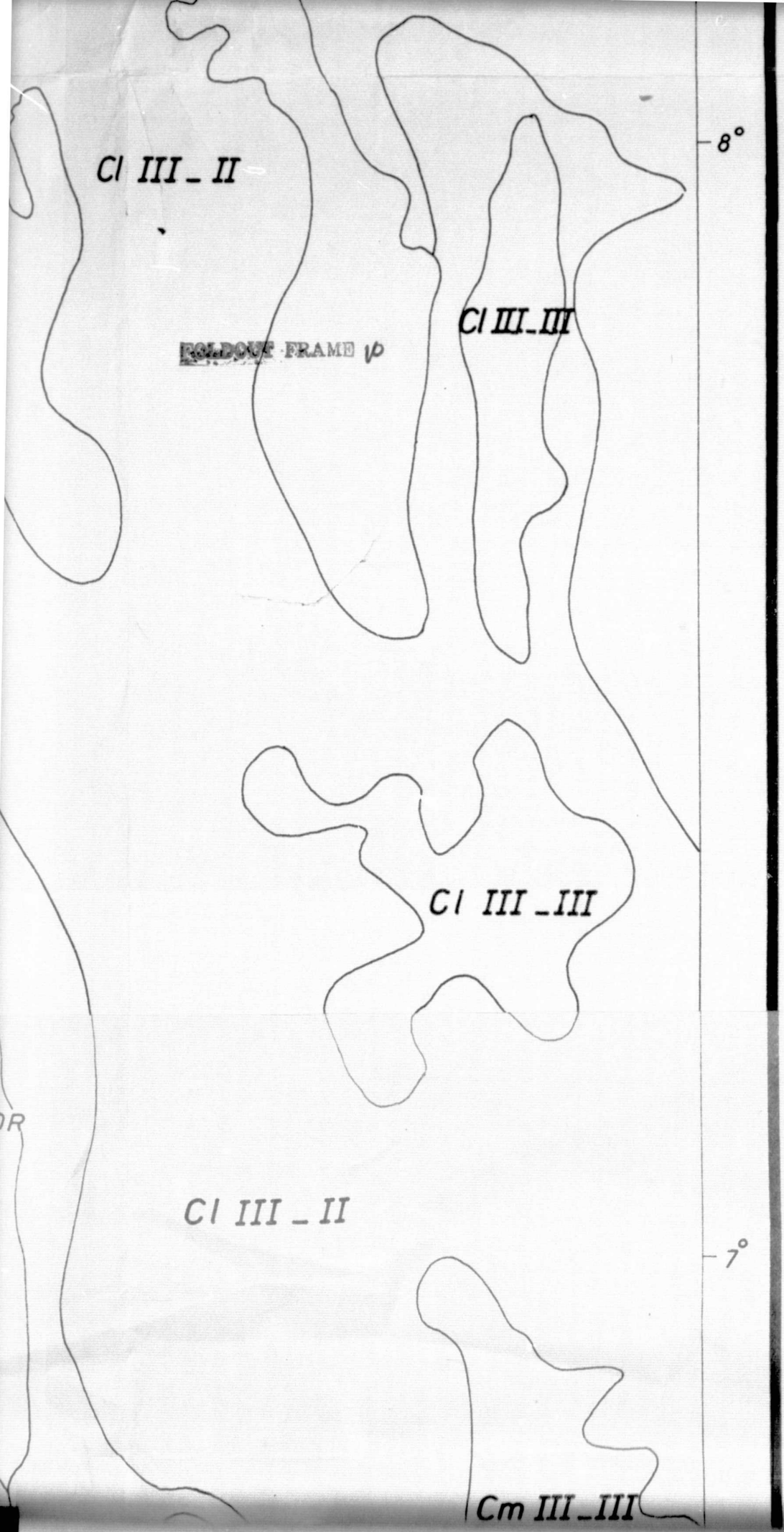

Ch II
Cl III_II
FmII_I
Cl II_I
Fp II_I
9°
FOLDOUT FRAME 6
BAHR EL JEBEL
EZ ZE
Fp II_
Fm¹ II.I
BAHR
Fs
Fs
Fm II_II


Ch III_II
Cm III_III
Ch III_II
Cl III _ III
FOLDOUT FRAME 6
Fs
Cl III.I
EZ ZERAF
Fs
Cl III_
CmIII_III
Cm III _ II
Fp II_I
m1 II.I
BAHR
Fs
Cl III_I
Cl
Fs
Ch_III_II
Cm III _ II


Cm III_III
II
9°
FOLDOUT FRAME 7
Cl III_II
Cl III_II
Cm III_II
Cl III_III
Ch III_III


Fm II_I
8°
FOLDOUT FRAME 8
Fm III_II
Fm III_II
Fm II_I
Fm² I_I
Fm² II_II
Cl III_II
Fm² II_II
Fp II_II
7°
Cl III_II
Cm III_II
Cm III_III
Fm¹ II_II
Cl III_II


Fs
Fs
Cm III _ II
Ch_III_II
Cl III _ II
FOLDOUT FRAME 4
ClIII_I
Fm2 I_I
Fm2 II_II
Fm2 II_II
Fp II_I
Cl III_I
KONGOR
Fp II_I
Fp II_I
III_II
Fm II_I
JONGLEI



5

FLOODING CONDITION

I_ NON FLOODED AREA

II_ RIVER FLOODING

I_ PERENNIAL FLOO

II_SEASONAL FLOO

III_ RUN OFF FLOODI

I- PERENNIAL FL

II_ SEASONAL FLO

III_SEASONAL FL

FOLDOUT FRAME 11

5 0 5 10 15 20 25 30 35Km

LEGEND

FLOODING CONDITION:

I_ NON FLOODED AREA

II_ RIVER FLOODING

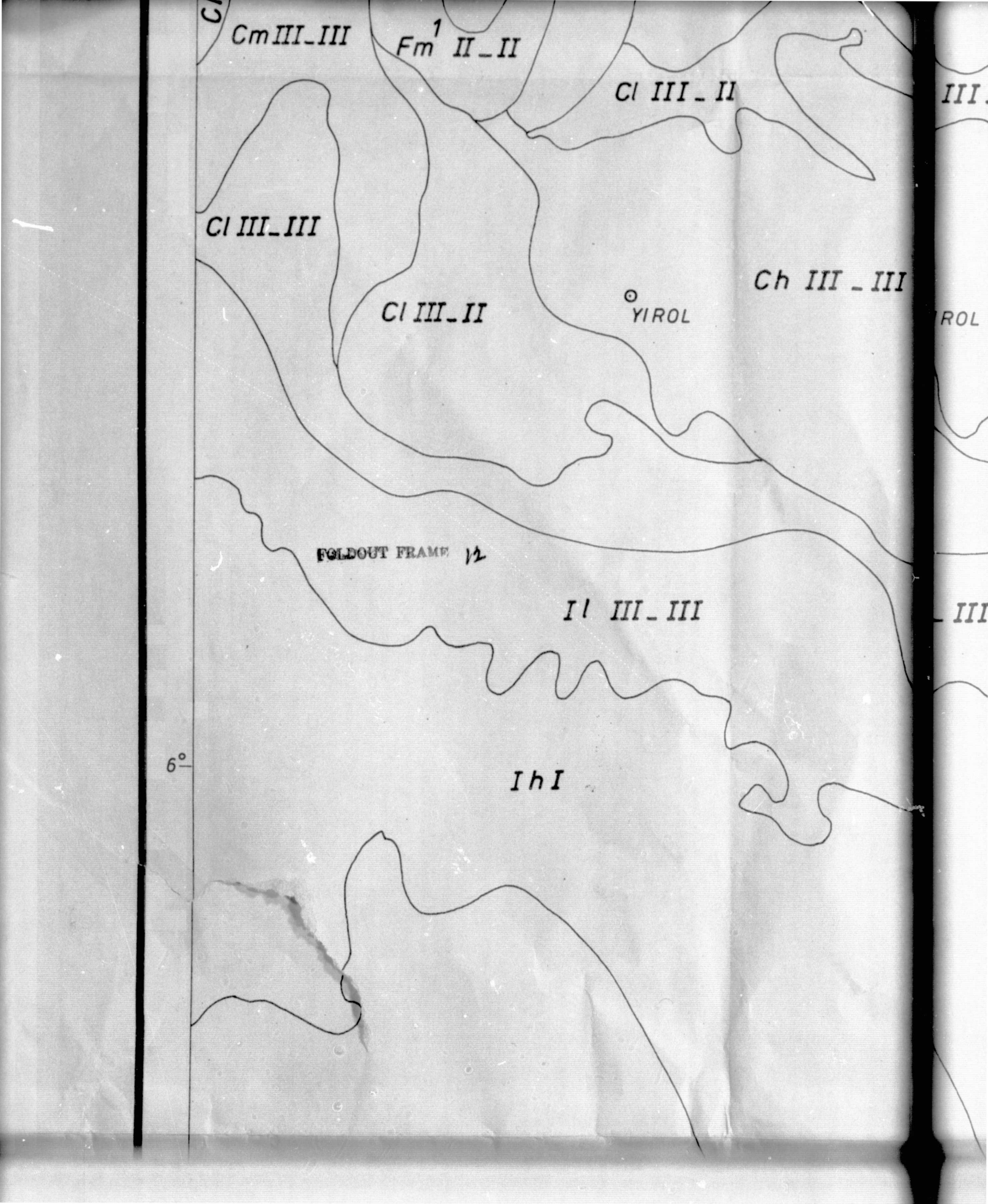
I_ PERENNIAL FLOODING

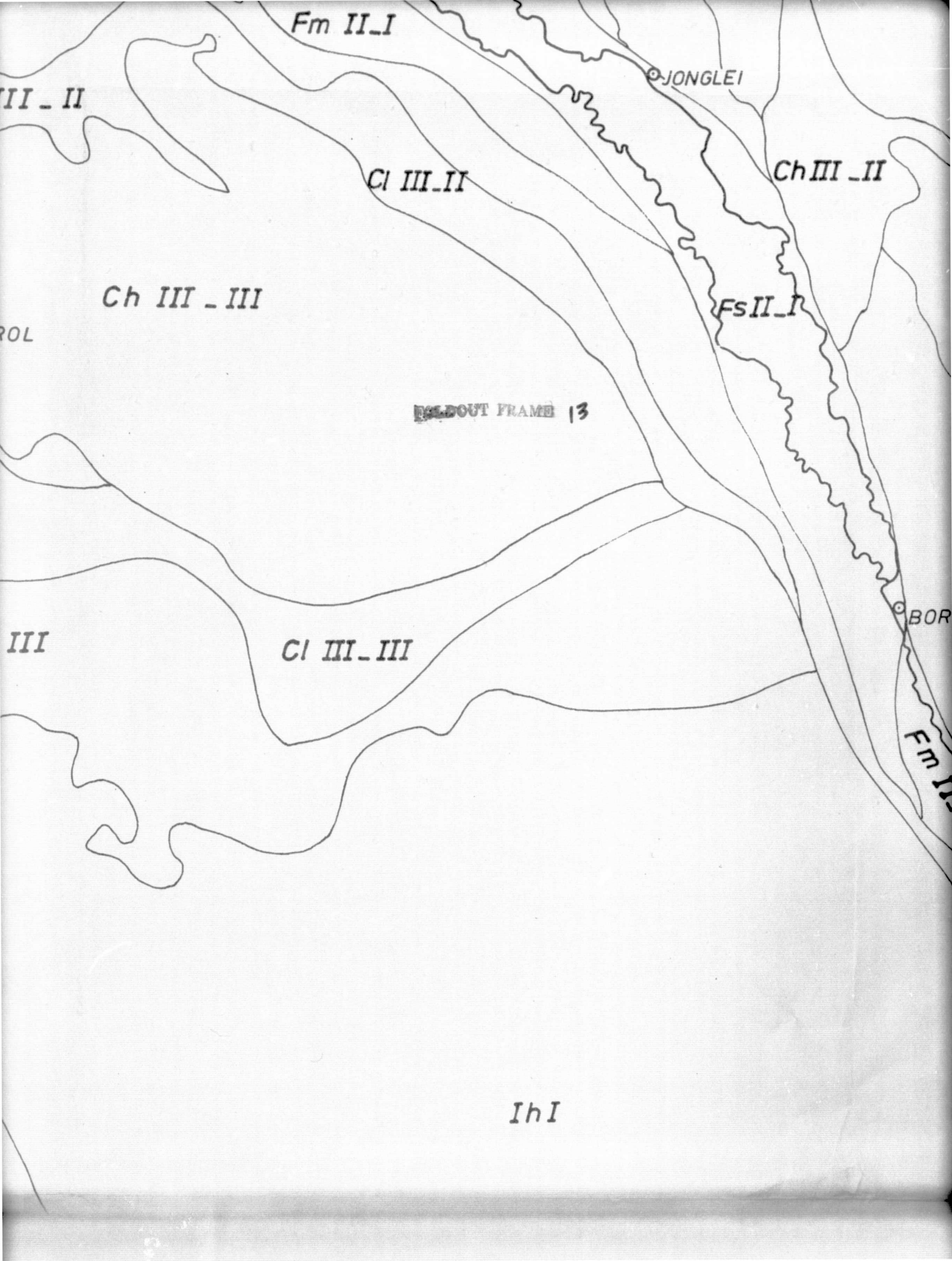
II_ SEASONAL FLOODING

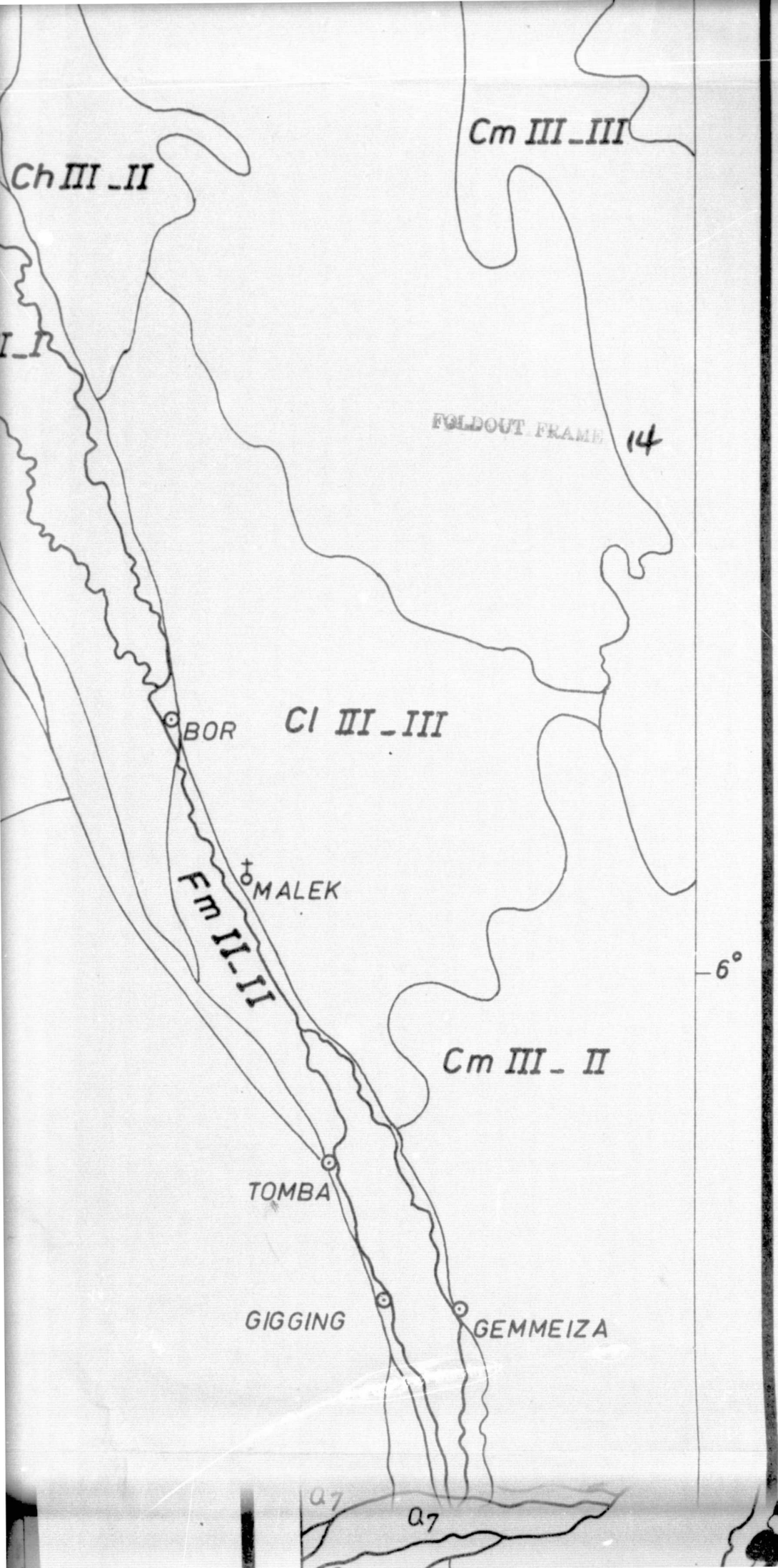
III_ RUN OFF FLOODING

I_ PERENNIAL FLOODING

II_ SEASONAL FLOODING


Cm III_III
Fm 1 II_II
Cl III_II
Cl III_III
Ch III_III
Cl III_II
YIROL
FOLDOUT FRAME 12
Il III_III
6°
Ih I


Fm II_I
JONGLEI
III _ II
Cl III_II
Ch III _II
Ch III _ III
Fs II_I
ROL
FOLDOUT FRAME 13
BOR
III
Cl III_III
Fm I
IhI



II_ SEASONAL FLOO

III_ SEASONAL FLOO

TERRAIN UNITS:

C_ CLAY PLAIN Cl

Cm

Ch

F_ EL SUDD PLAIN Fb

Fp

Fm

Fs

I_ LATERITIC COUNTRY

Il

Ih

B_ BASEMENT UPLAND

CITIES AND TOWNS

a4 a2

II_ SEASONAL FLOODING

III_ SEASONAL FLOODING WITH SHALLOW WATER COVERAGE

RAIN UNITS:

CLAY PLAIN

Cl_ PLAIN OF LOWER ALTITUDE

Cm_ PLAIN OF MODERATE ALTITUDE

Ch_ PLAIN OF HIGH ALTITUDE

EL SUDD PLAIN

Fb_ BRAIDING CHANNEL COMPLEX

Fp_ FLOOD PLAIN

Fm_ SWAMPS WITH NOTABLE MEANDERS

Fm^1 DENSE VEGETATION

Fm^2 LESS DENSE VEGETATION

Fs_ OPEN WATR, LAKES, LAGOONS etc.

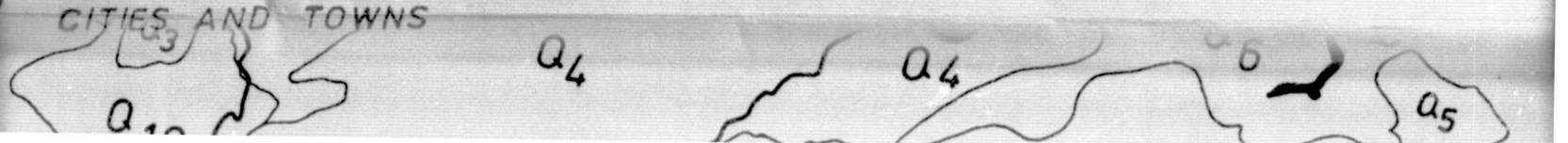
LATERITIC COUNTRY

Il_ LOW LATERITIC PLAIN

Ih_ HIGH AND UNDULATING LATERITIC LAND

BASEMENT UPLAND

CITIES AND TOWNS

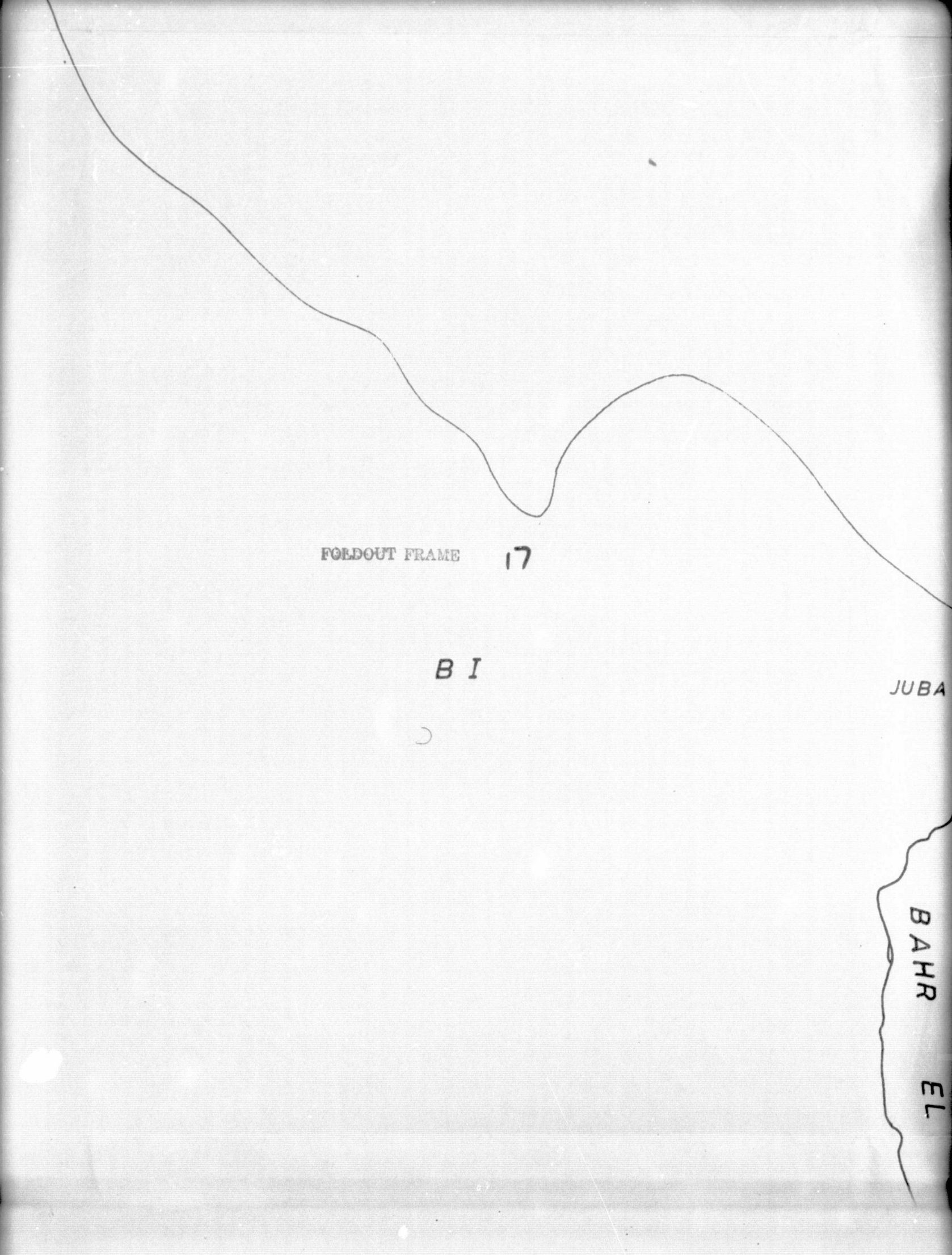


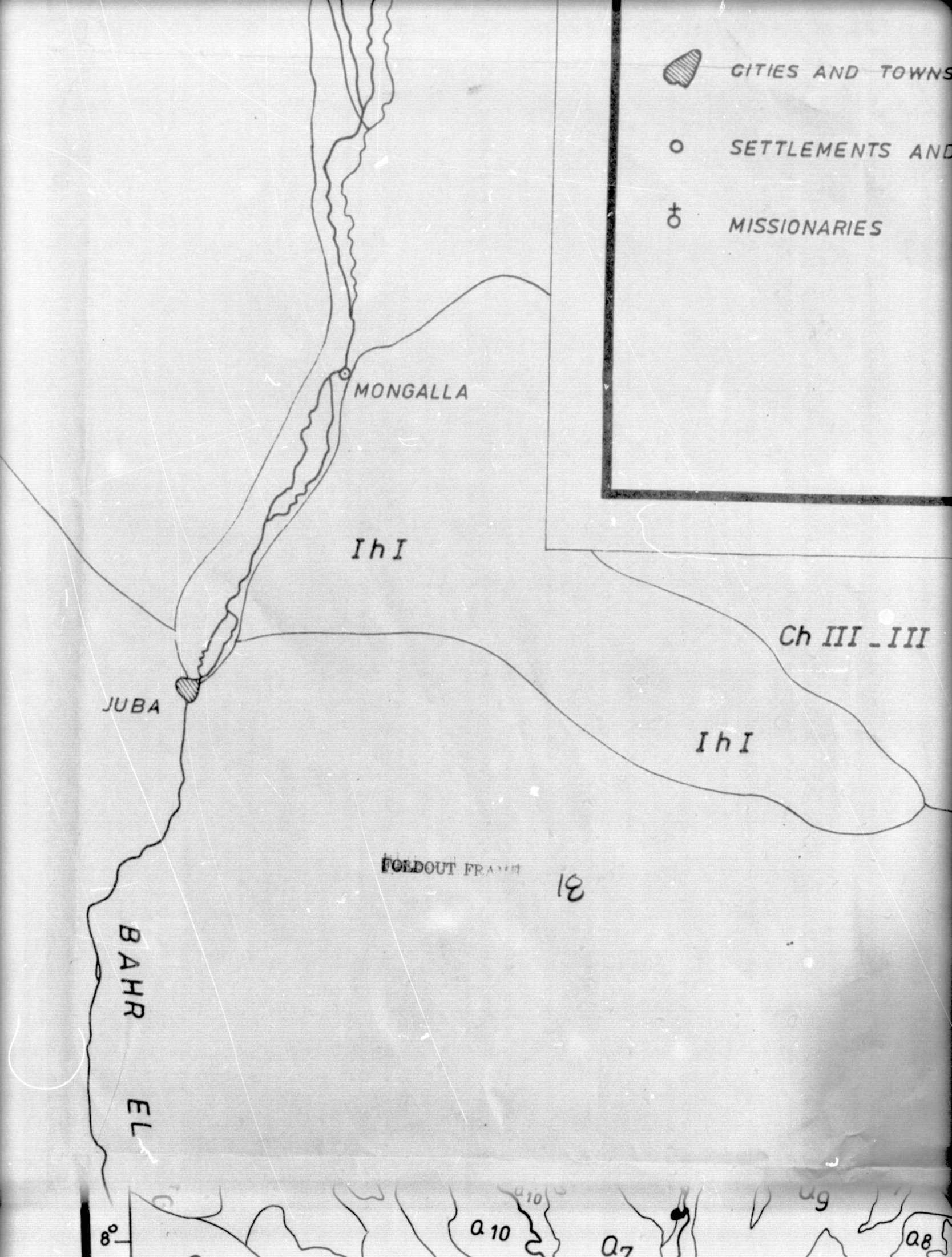
B I

FOLDOUT FRAME 16

5°

a_5


FOLDOUT FRAME 17
B I
JUBA
BAHR
EL

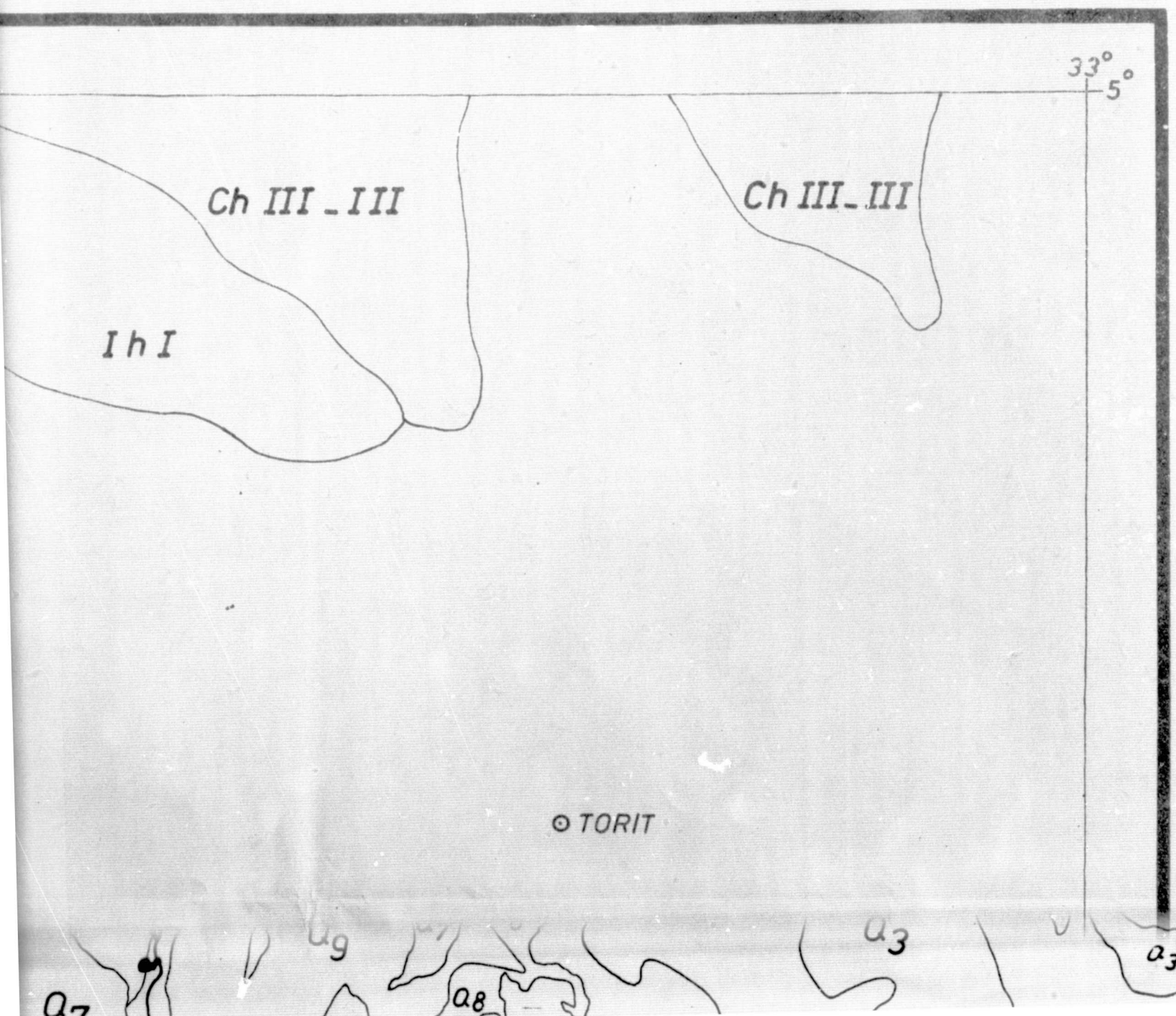

CITIES AND TOWNS
SETTLEMENTS AND
MISSIONARIES
MONGALLA
IhI
Ch III _ III
JUBA
IhI
FOLDOUT FRAME
BAHR EL
8°
a10
a7
a9
a8

CITIES AND TOWNS

SETTLEMENTS AND SMALE TOWNS

MISSIONARIES

FOLDOUT FRAME 19



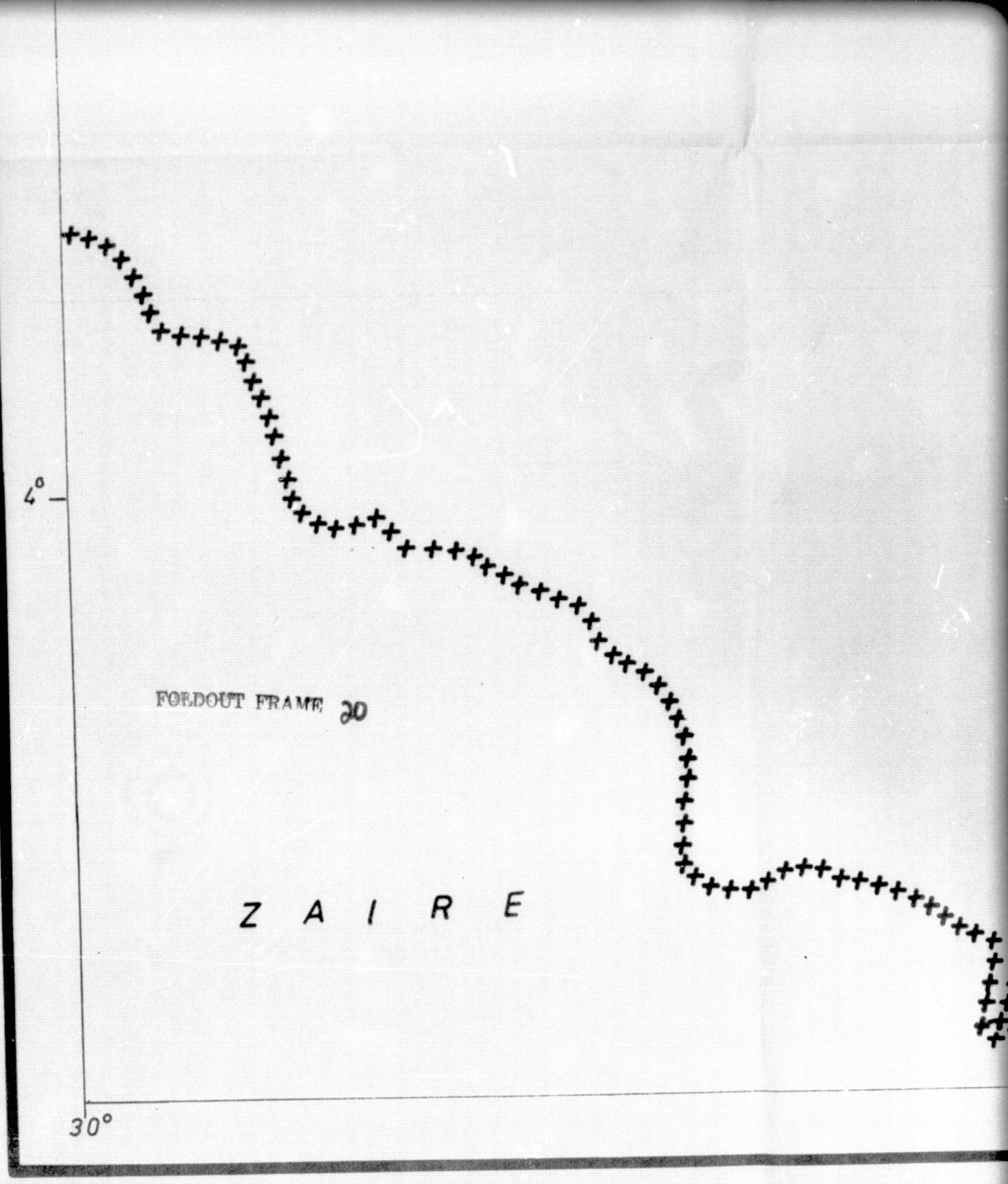
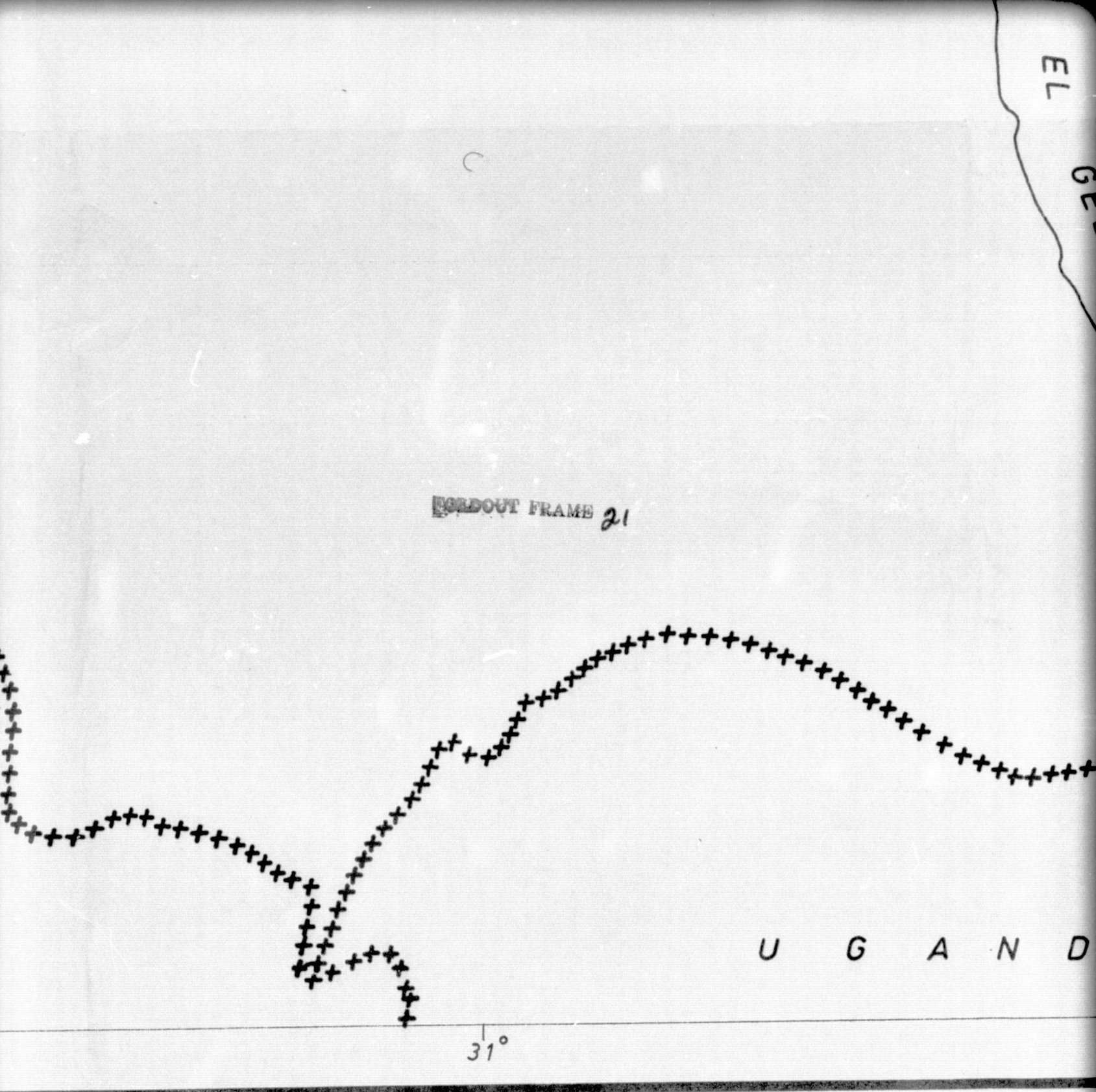
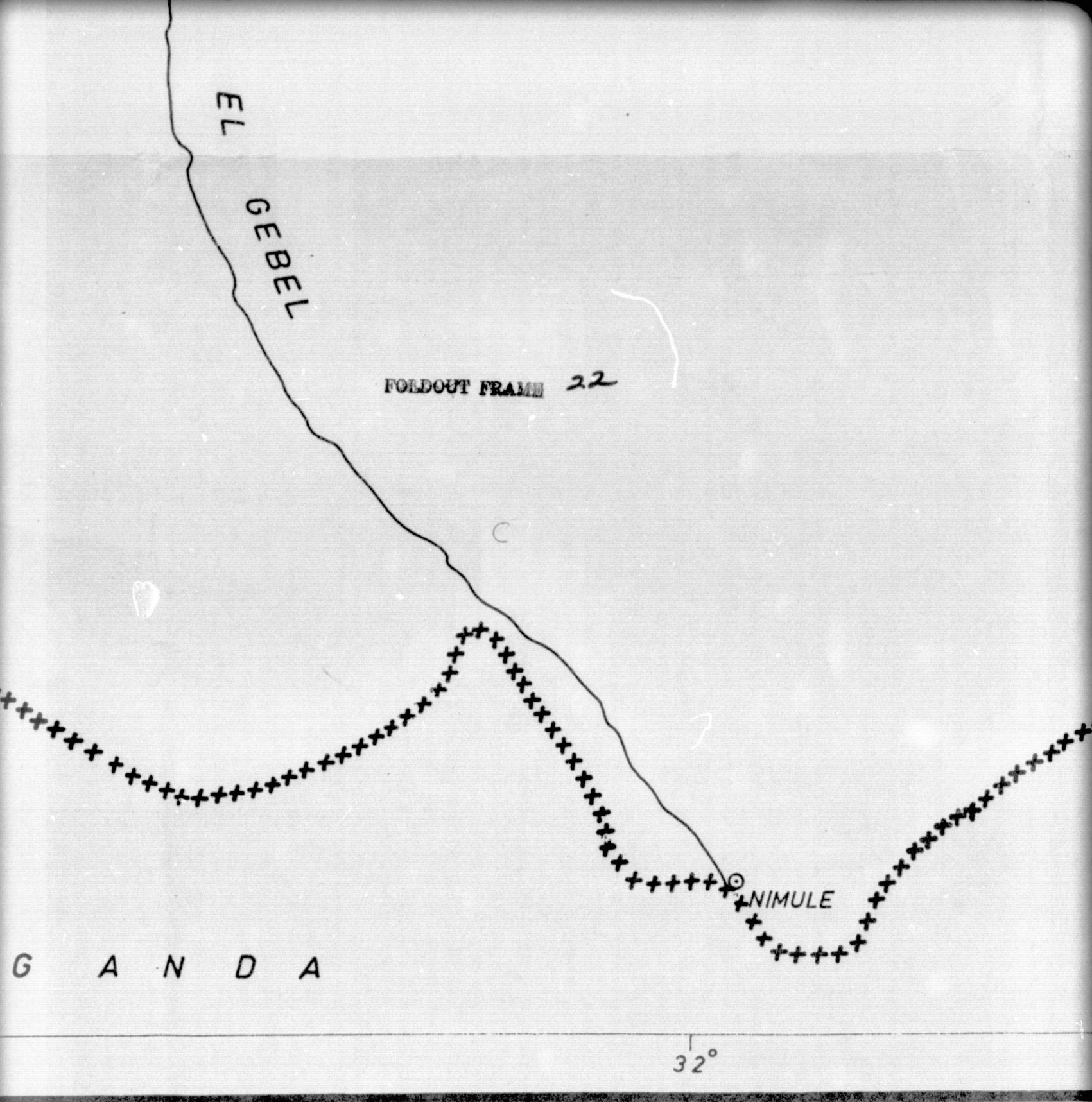


FIG. 6. MAP SHOWING THE GEN
SUDAN. (FROM LANDSAT



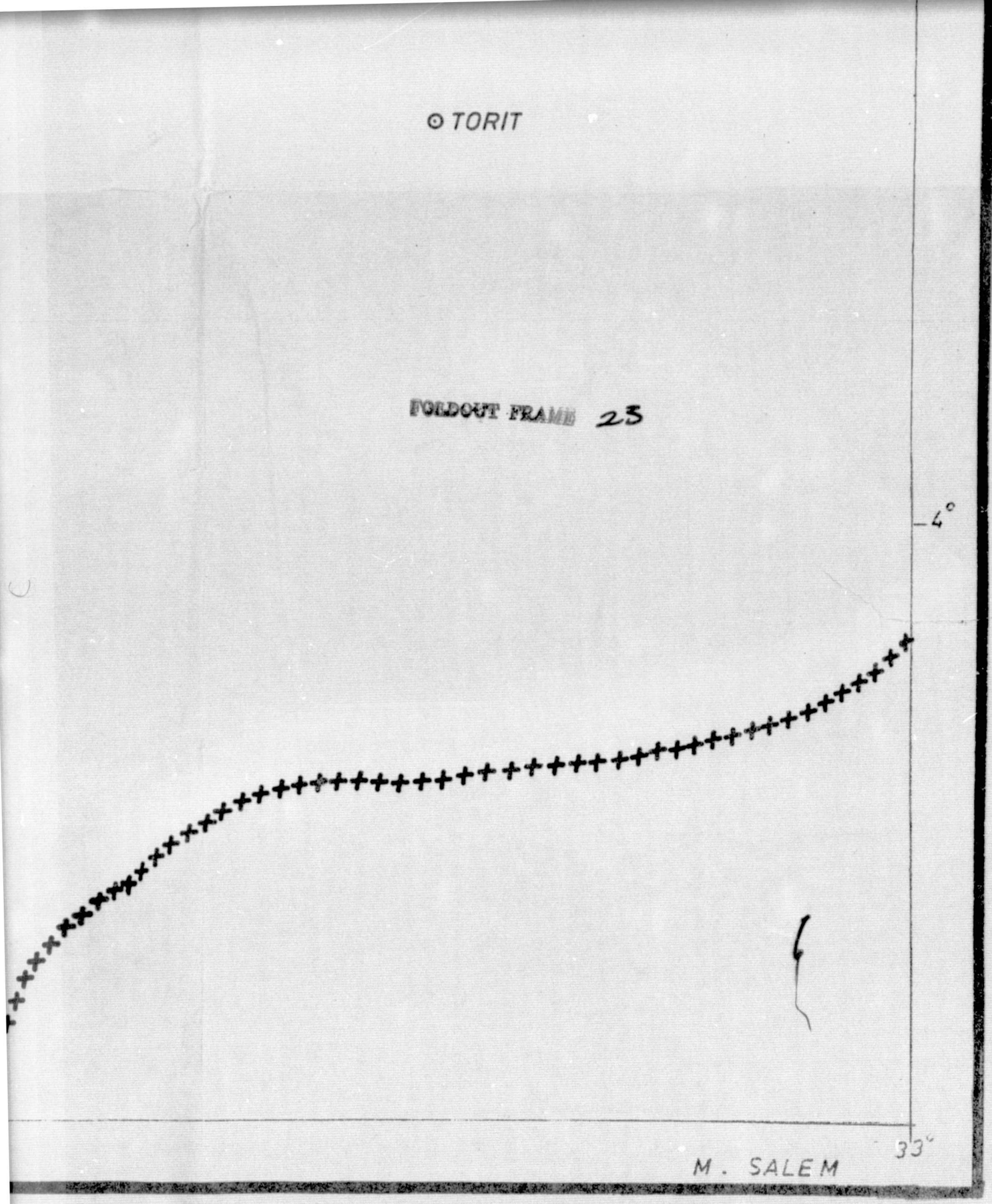
NG THE GENERAL SURFACE WATER CONDI

OM LANDSAT_1 SATELLITE IMAGES, FEB., C



TER CONDITION IN JONGLEI CANAL PROJECT

ES, FEB., OCT. AND NOV. 1973).

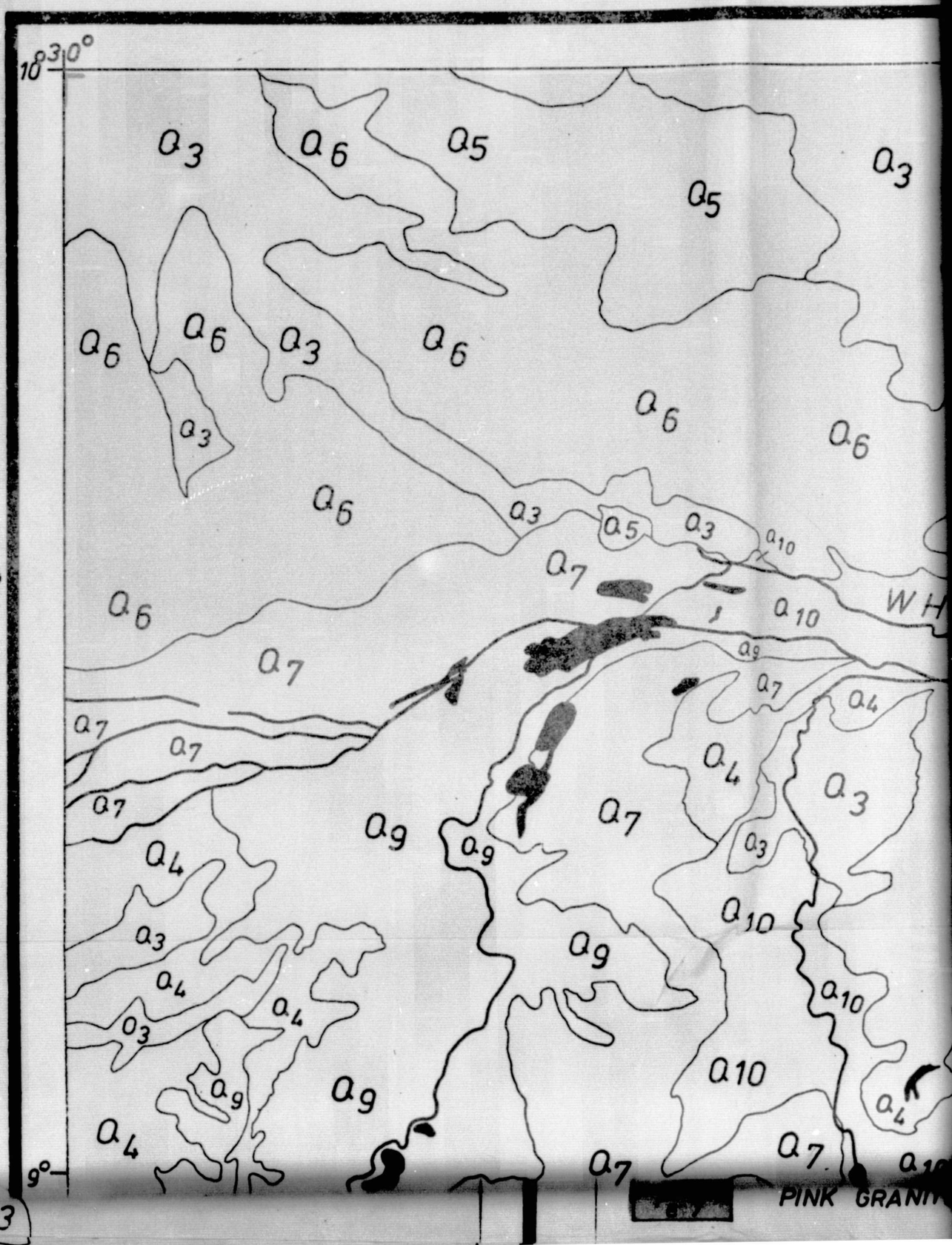


PROJECT AREA, SOUTHERN

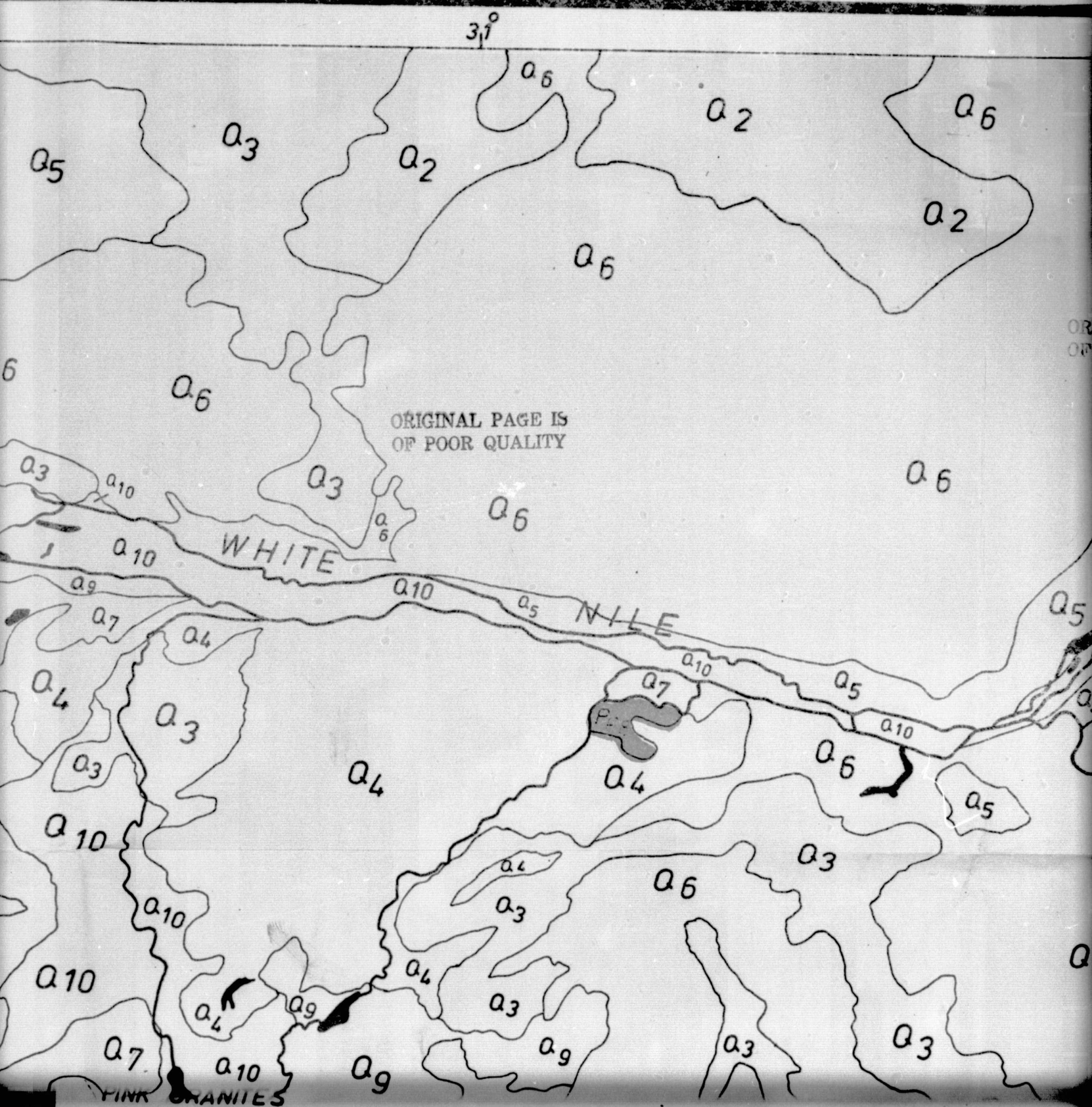
REMOTE SENSING CENTER

FOLDOUT FRAME 1 ACADEMY OF SCIENTIFIC RESEARCH AND T

ORIGINAL PAGE IS
OF POOR QUALITY

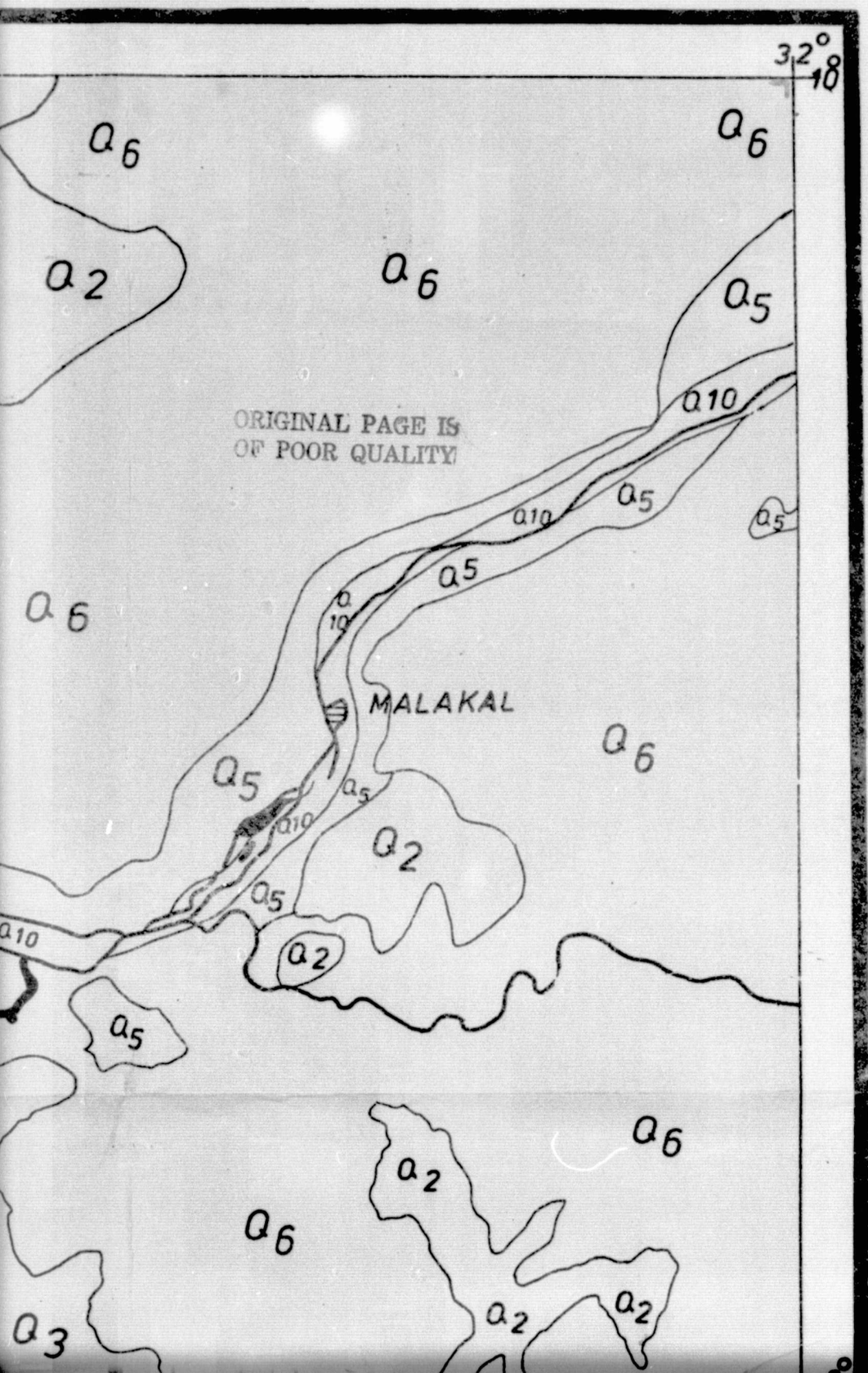


FOLDOUT FRAME 2



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OF POOR QUALITY

FOLDOUT FRAME 3



MINISTRY OF IRRIGATIO
ARAB REPUBLIC OF EGYPT

THE PE
COMM

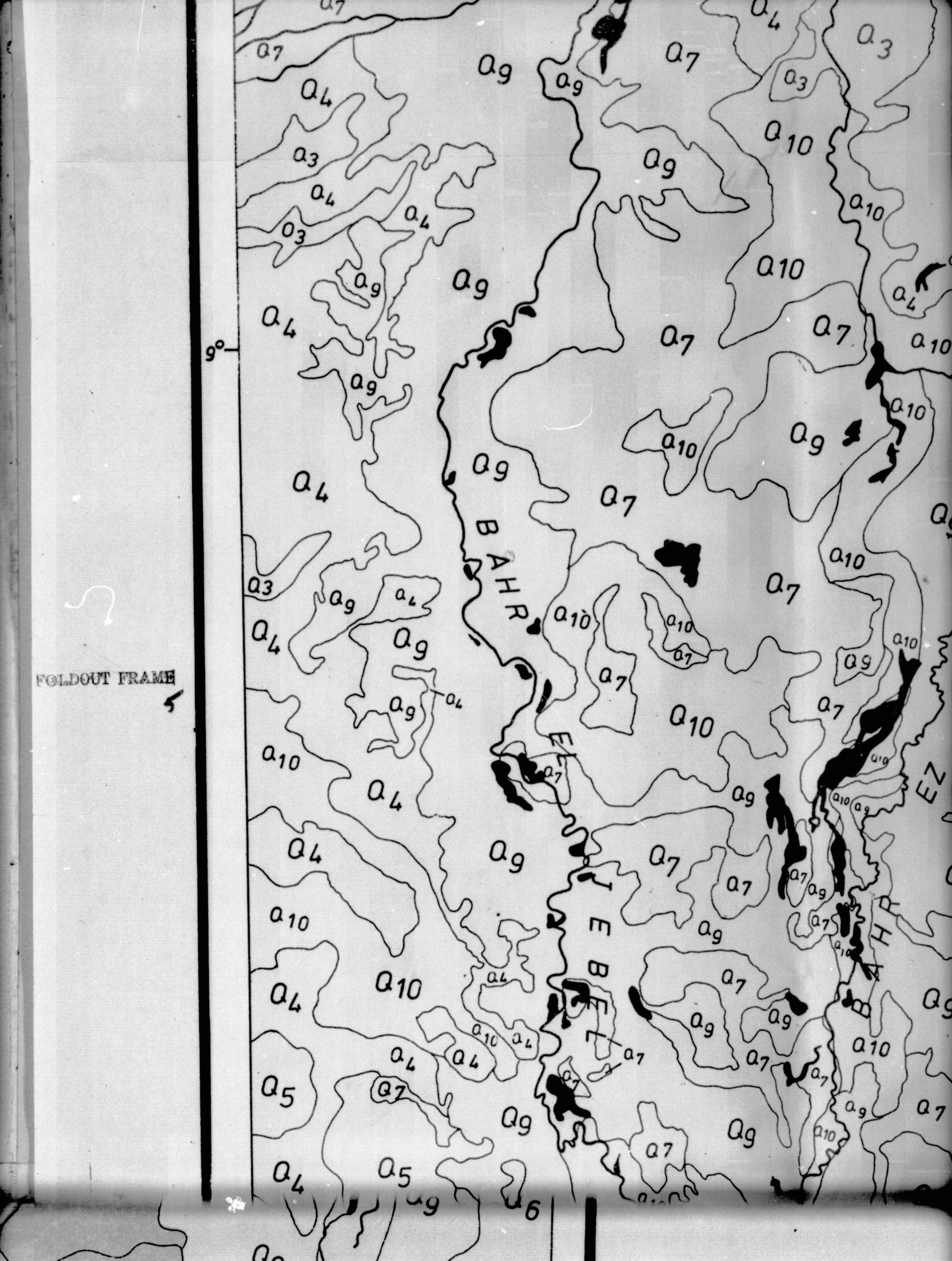
MINISTRY OF IRRIGATION,
ARAB REPUBLIC OF EGYPT

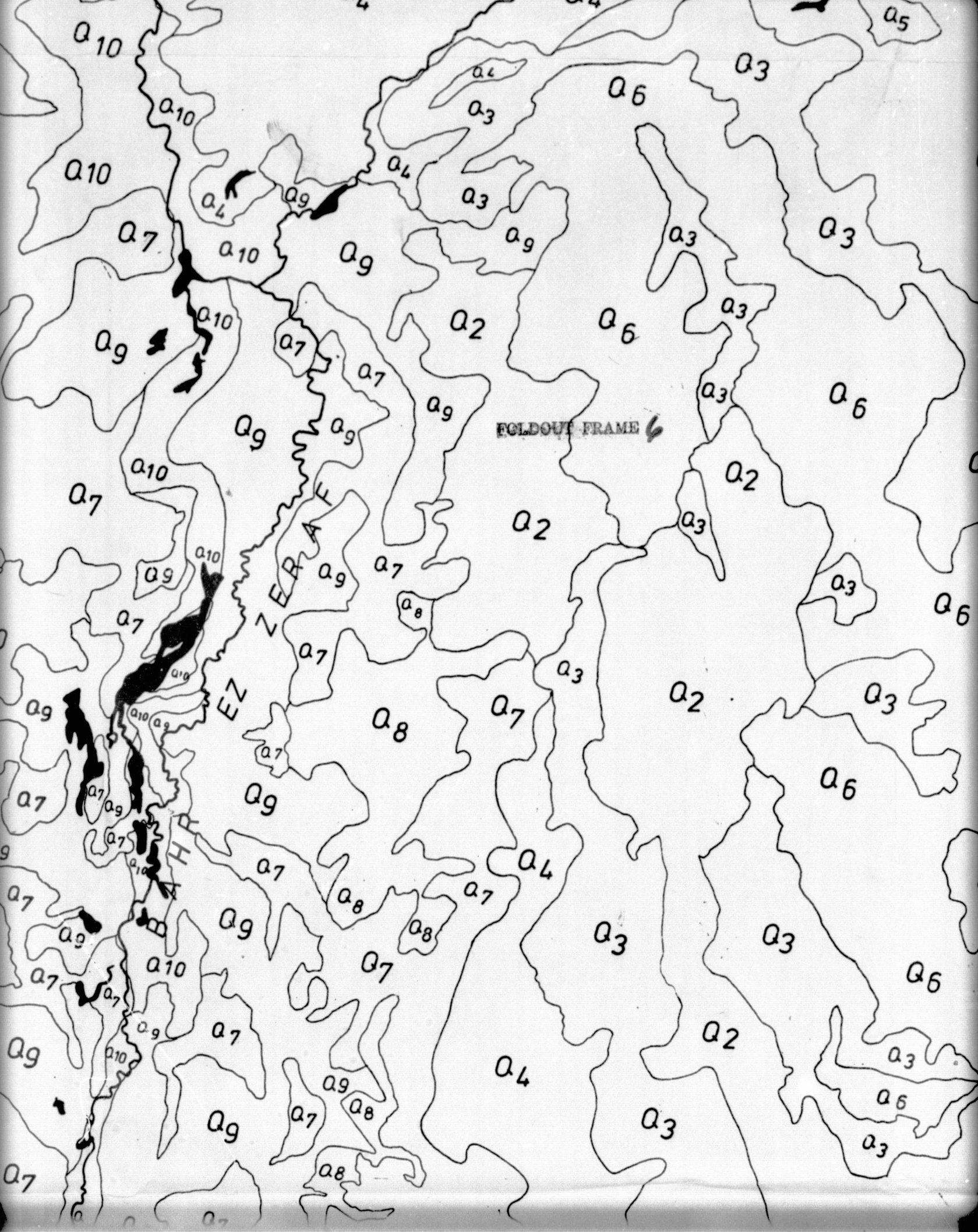
MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

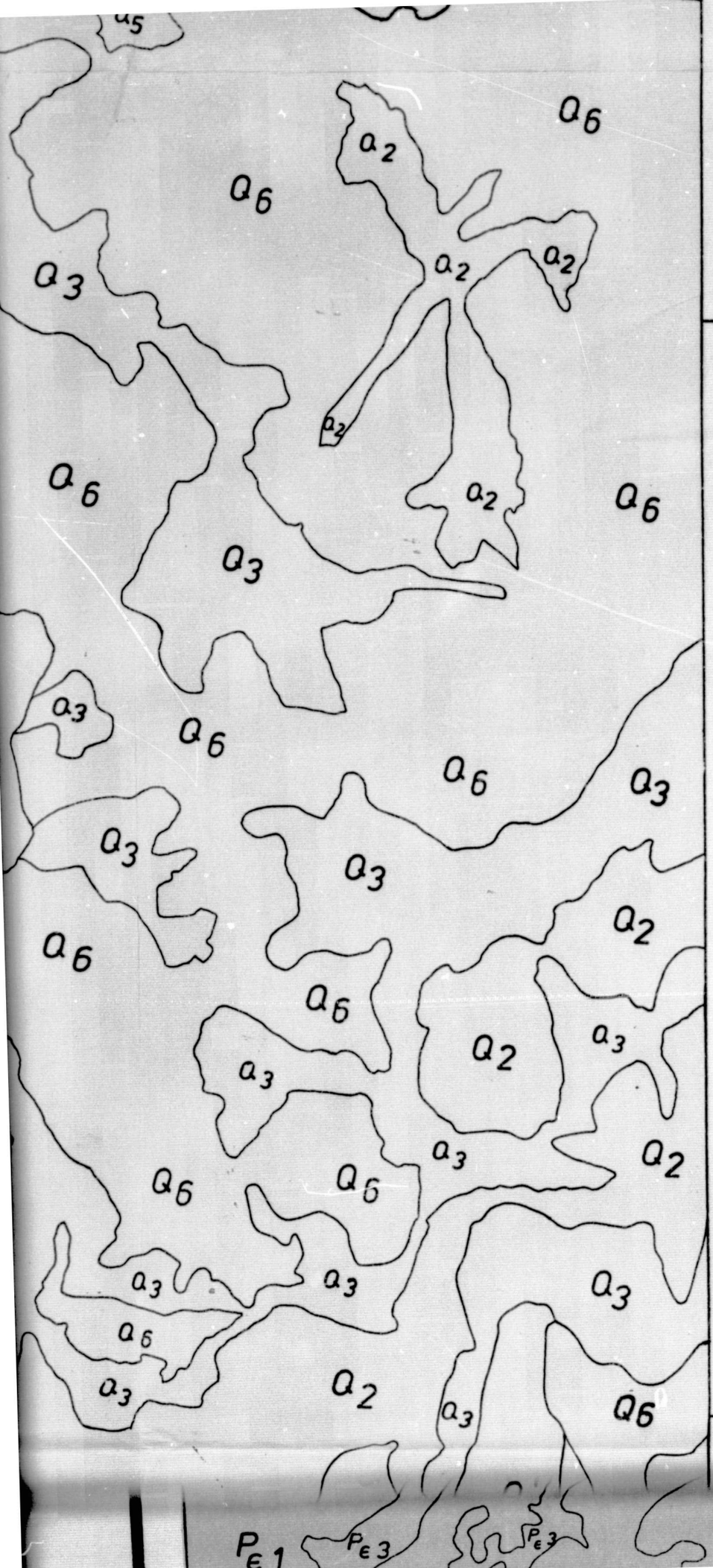
THE PERMANENT JOINT TECHNICAL COMMISSION FOR NILE WATERS

FOLDOUT FRAME 4

ORIGINAL PAGE IS
OF POOR QUALITY


9°
BAHR EL GHAZEL
BAHR EL ARAB
FOLDOUT FRAME


FOLDOUT FRAME 6
ZERAF
EZ
AHR



FOLDOUT FRAME 7

— QUATERNARY, MAINLY

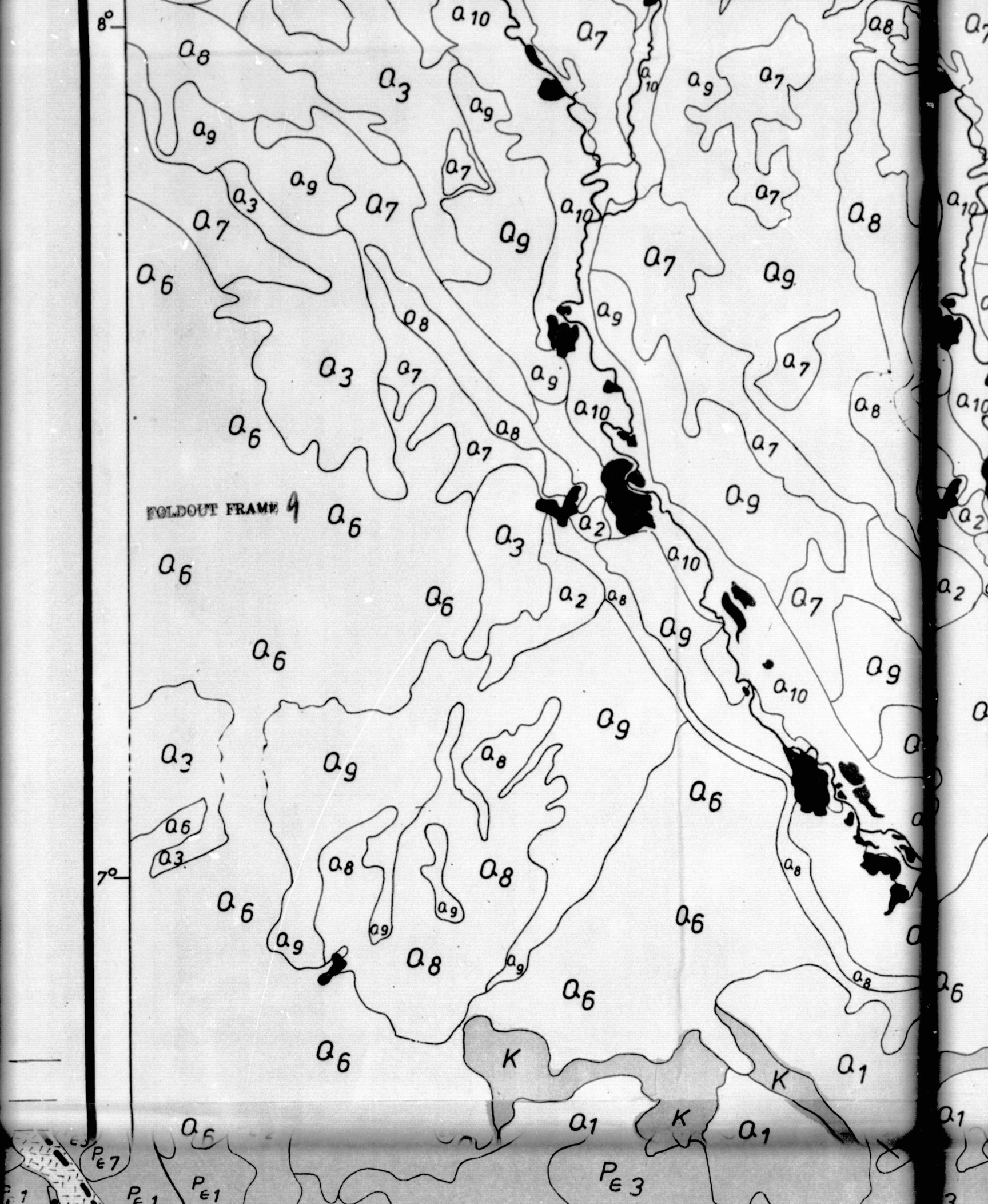
Q_{11}	WADIS FILLED ALLUVIUM, DRA
Q_{10}	SOIL, PERENNI DEEPER WAT
Q_9	SOIL, PERENNI RELATIVELY SH
Q_8	SOIL, FLOODED DEEPER WAT
Q_7	SOIL, FLOODED RELATIVELY SH
Q_6	FINE CLAY
Q_5	CLAY AND SILT
Q_4	SILT

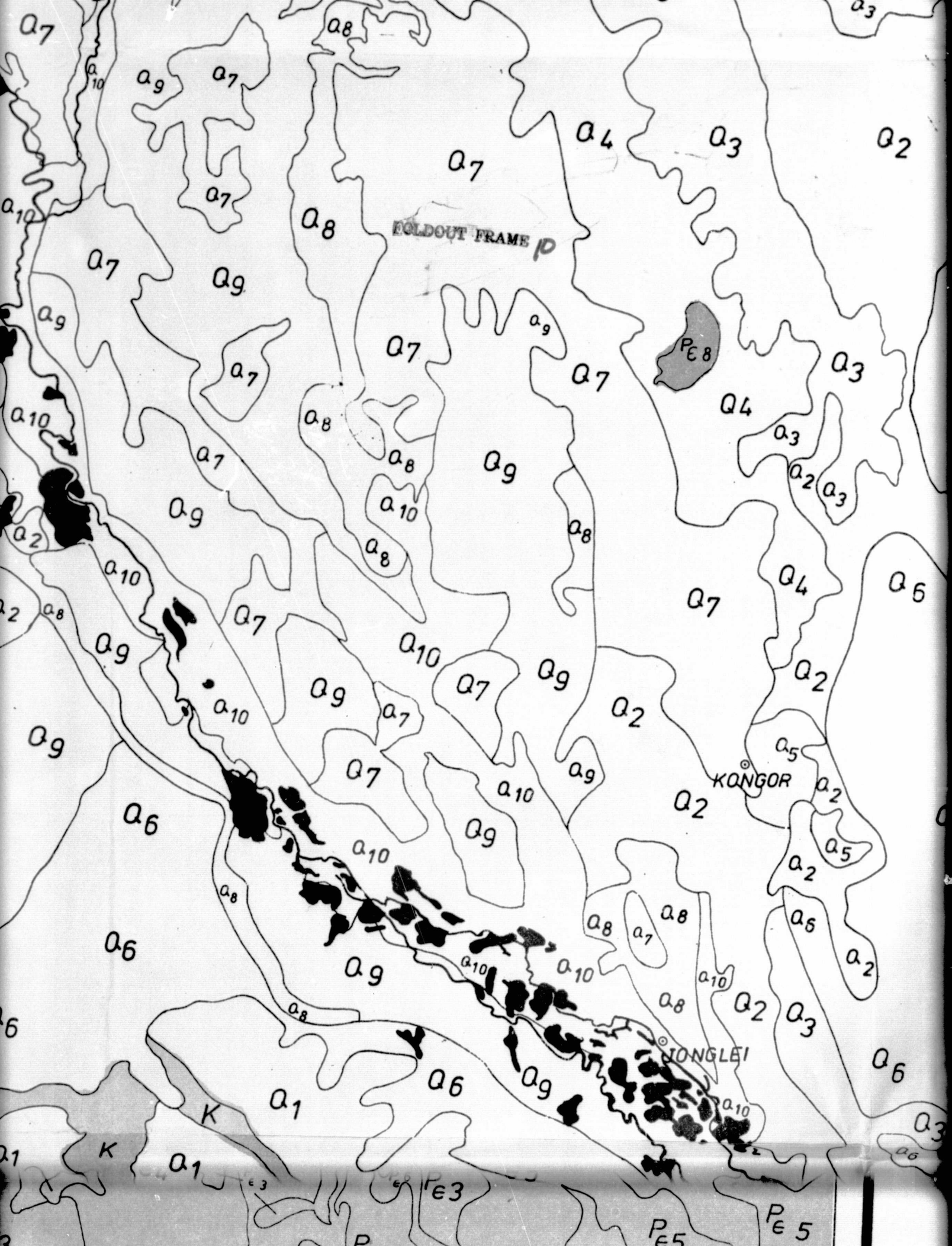
LEGEND

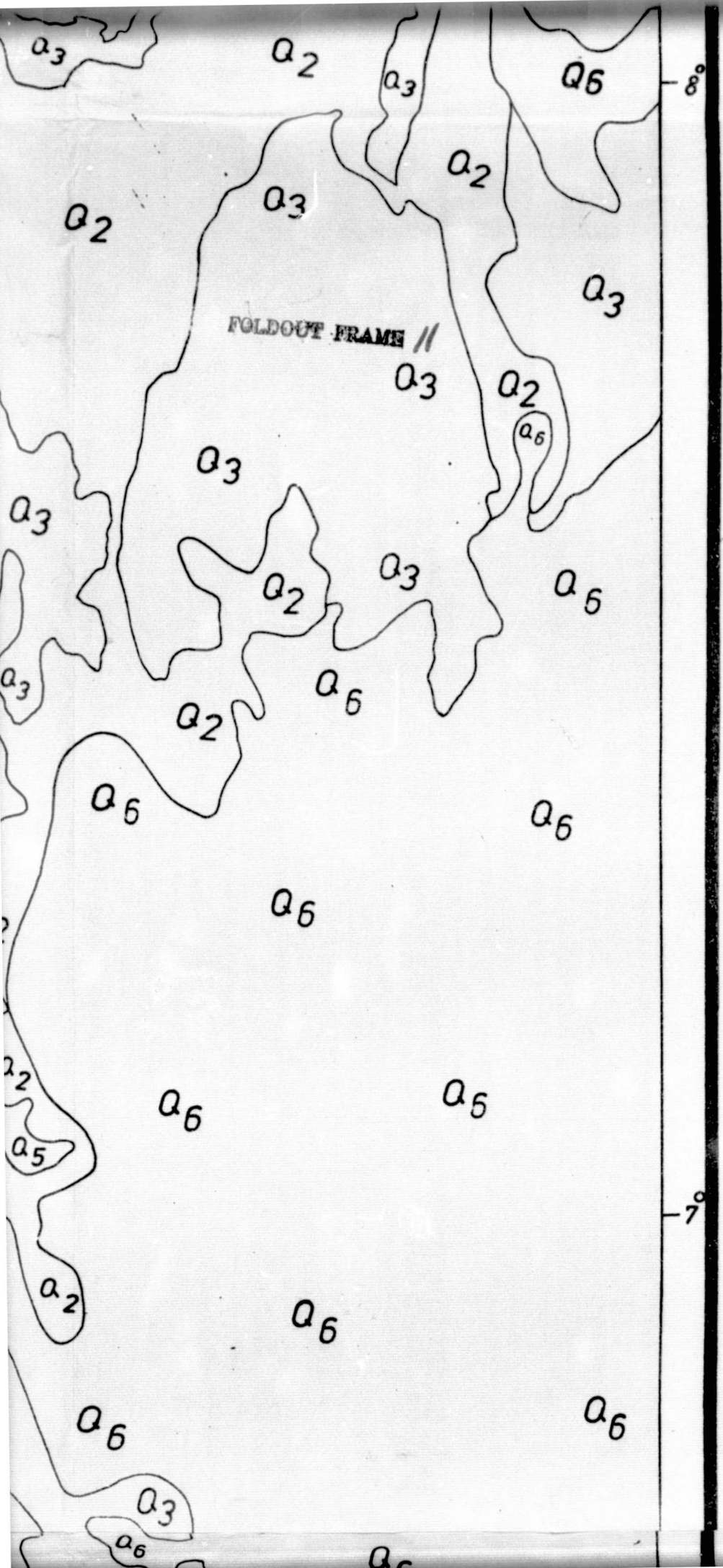
Q_{11}	WADIS FILLED WITH RELATIVELY COARSE ALLUVIUM, DRAINING MAINLY BASEMENT
Q_{10}	SOIL, PERENNIALLY FLOODED UNDER DEEPER WATER
Q_9	SOIL, PERENNIALLY FLOODED UNDER RELATIVELY SHALLOW WATER
Q_8	SOIL, FLOODED IN WET SEASON, UNDER DEEPER WATER
Q_7	SOIL, FLOODED IN WET SEASON, UNDER RELATIVELY SHALLOW WATER
Q_6	FINE CLAY
Q_5	CLAY AND SILTY CLAY
Q_4	SILT

QUATERNARY, MAINLY

$P_{\epsilon 2}$ $P_{\epsilon 3}$ $P_{\epsilon 2}$ $P_{\epsilon 3}$ $P_{\epsilon 7}$ $P_{\epsilon 1}$ $P_{\epsilon 1}$


8°
7°
FOLDOUT FRAME 4
a10
a7
a8
a3
a9
a6
a2
K
a1
Pε7
Pε1
Pε3


FOLDOUT FRAME 10
KONGOR
JONGLEI



QUA

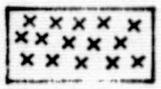
Q_4	SILT
Q_3	SANDY CLAY
Q_2	SAND
Q_1	COARSE SAND A
L_2	LATERITIC EXPOS
L_1	LATERITIC EXPOSU
K	YIROL FORMATION

PHANEROZOIC EXCLUDING CRETACEOUS SEDIMENTARY COVER

$P_{\epsilon 8}$	GRANITOIDS
$P_{\epsilon 7}$	PINK GRANITES

4	SILT
3	SANDY CLAY
2	SAND
1	COARSE SAND AND GRAVEL
2	LATERITIC EXPOSURES ; APPARENTLY LOCALLY TRANSPORTED
1	LATERITIC EXPOSURES ; MAINLY IN SITU
K	YIROL FORMATION

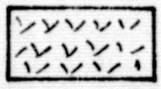
FOLDOUT FRAME 12



SYENITE , GRANITE AND SMALL IGNEOUS BODIES

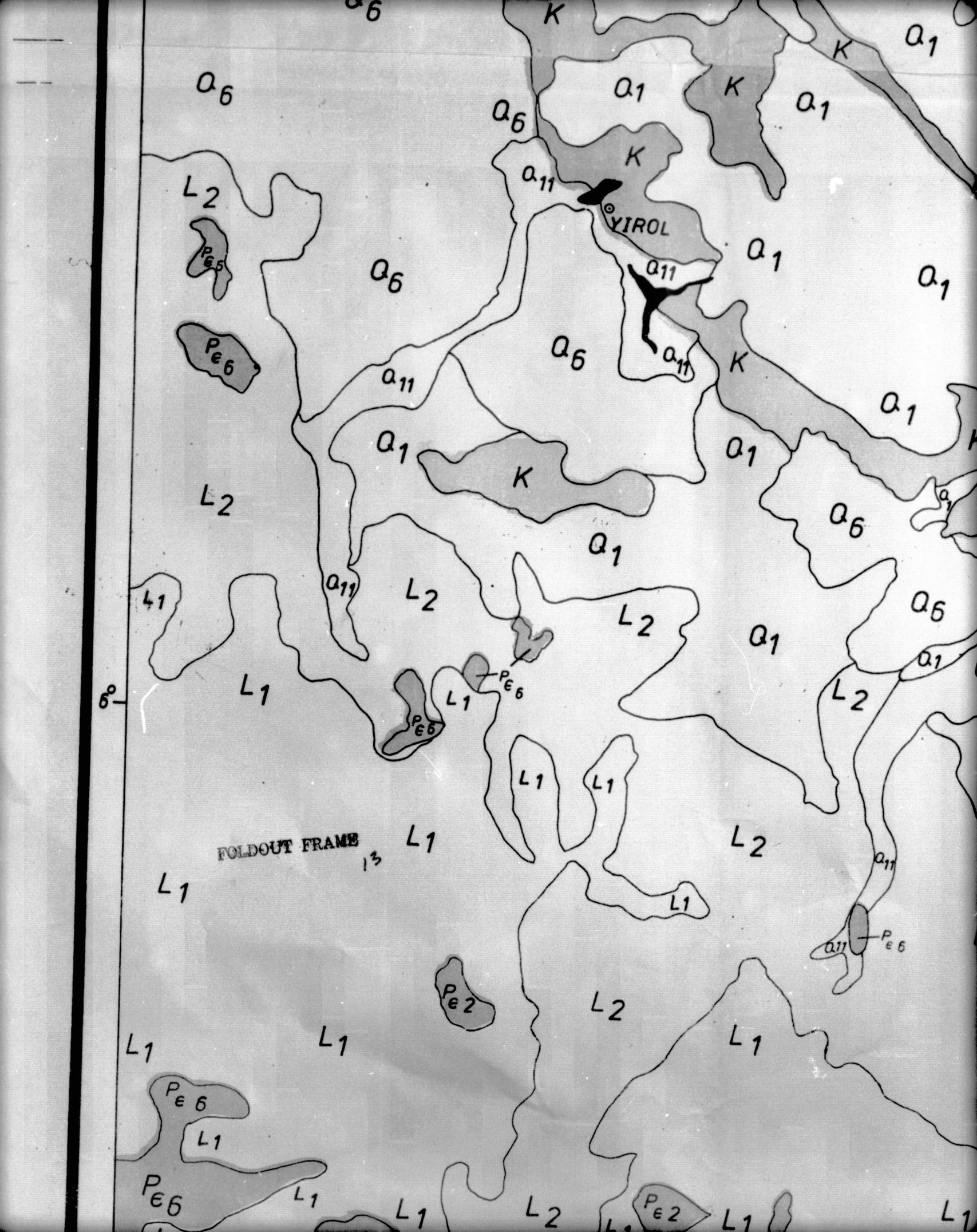


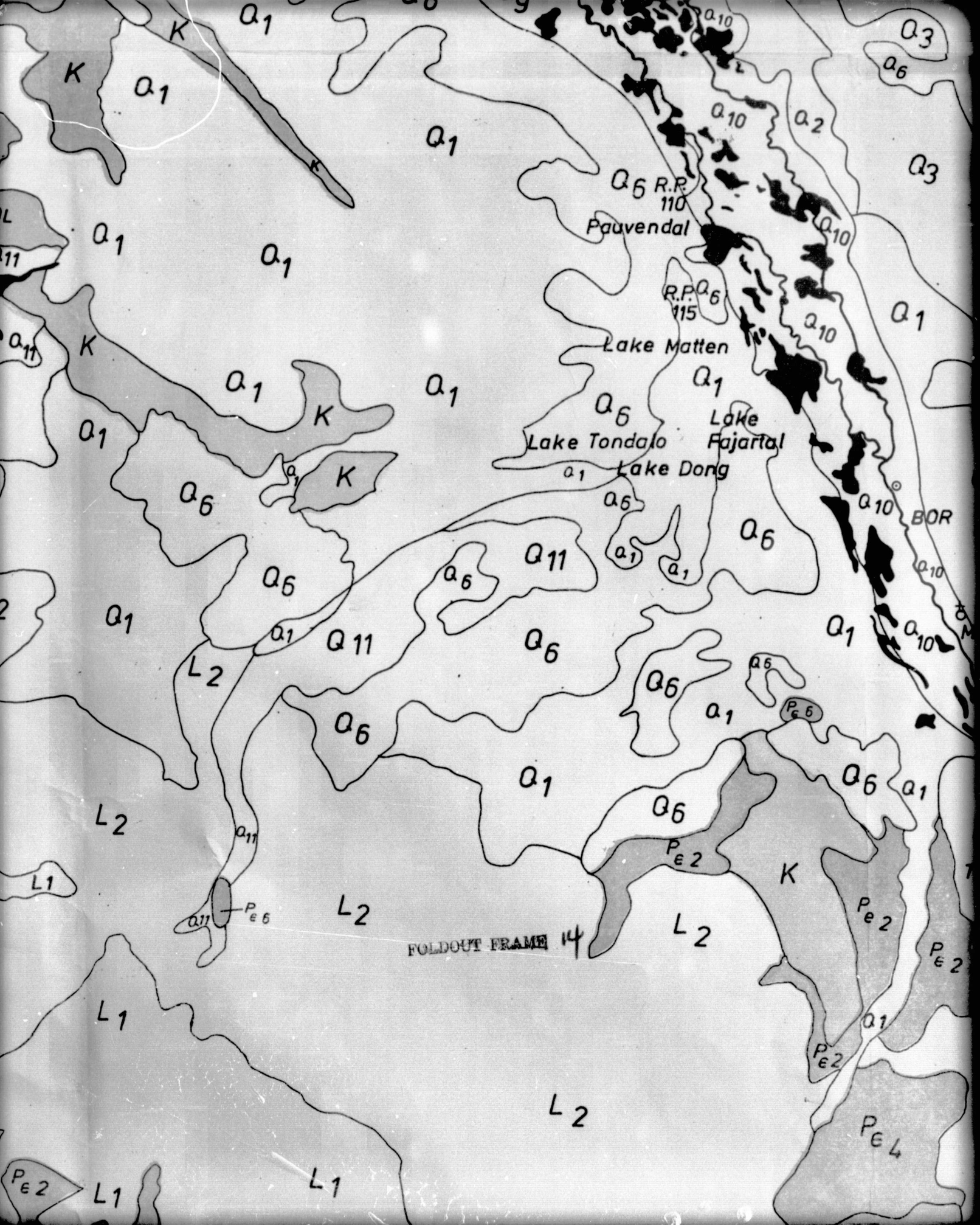
PORPHYRY AND OTHER DYKES

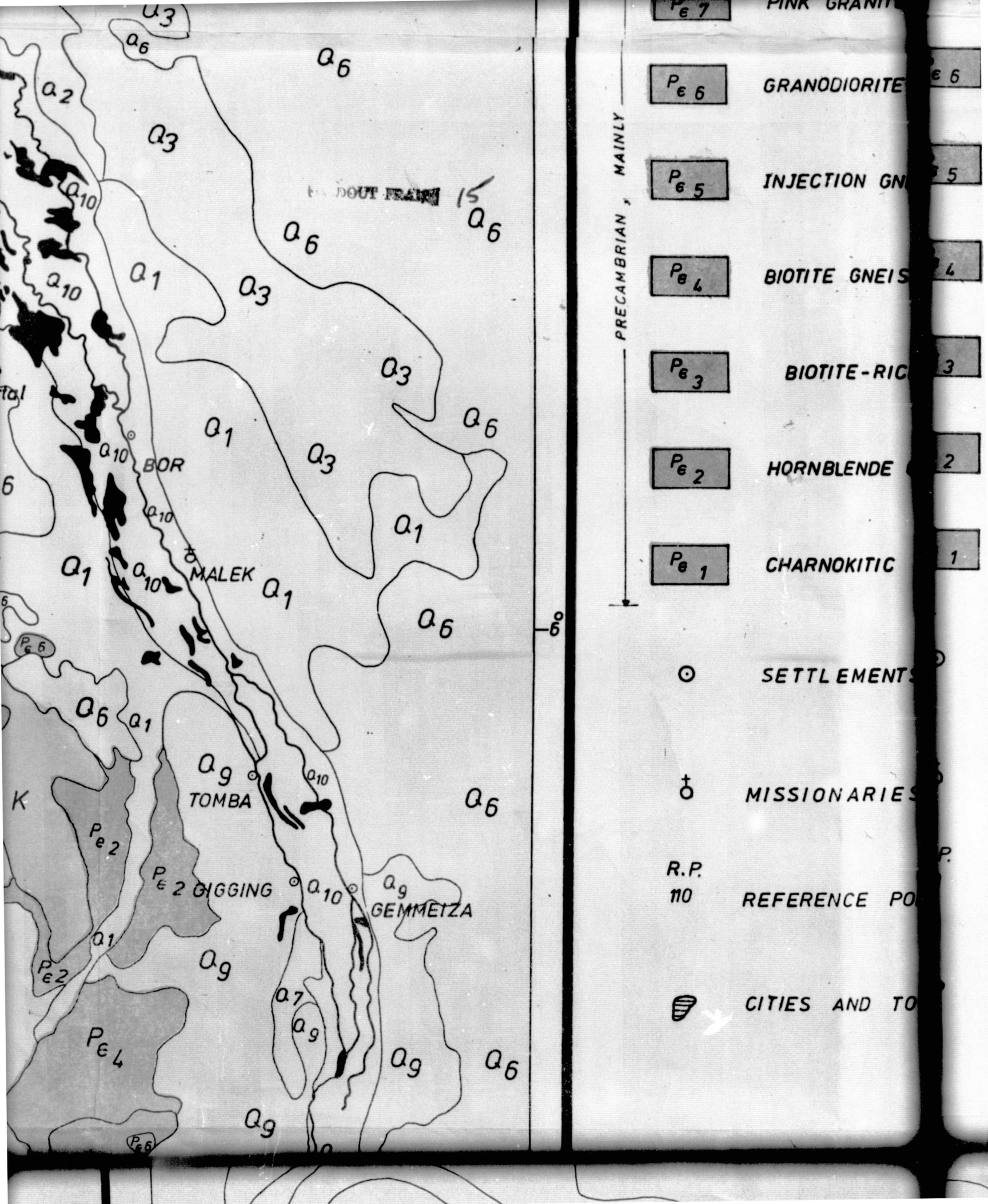


QUARTZITE ON FAULT ZONES

ε 8	GRANITOIDS
ε 7	PINK GRANITES


K
a_1
a_6
a_{11}
YIROL
L_2
$P_{\epsilon 6}$
L_1
$P_{\epsilon 2}$
6°
FOLDOUT FRAME 13


R.P. 110
Pauvendal
R.P. 115
Lake Matten
Lake Tondalo
Lake Fajartal
Lake Dong
BOR
FOLDOUT FRAME 14


PRECAMBRIAN, MAINLY
PINK GRANIT
GRANODIORITE
INJECTION GN
BIOTITE GNEIS
BIOTITE-RIC
HORNBLENDE
CHARNOKITIC
SETTLEMENT
MISSIONARIES
REFERENCE PO
CITIES AND TO
BOR
MALEK
TOMBA
GIGGING
GEMMEIZA
6°

6 GRANODIORITE-DIORITE-GREY GRANITE COMPLEX

5 INJECTION GNEISSES

4 BIOTITE GNEISSES

3 BIOTITE-RICH GNEISSES

2 HORNBLENDE GNEISSES

FOLDOUT FRAME 6

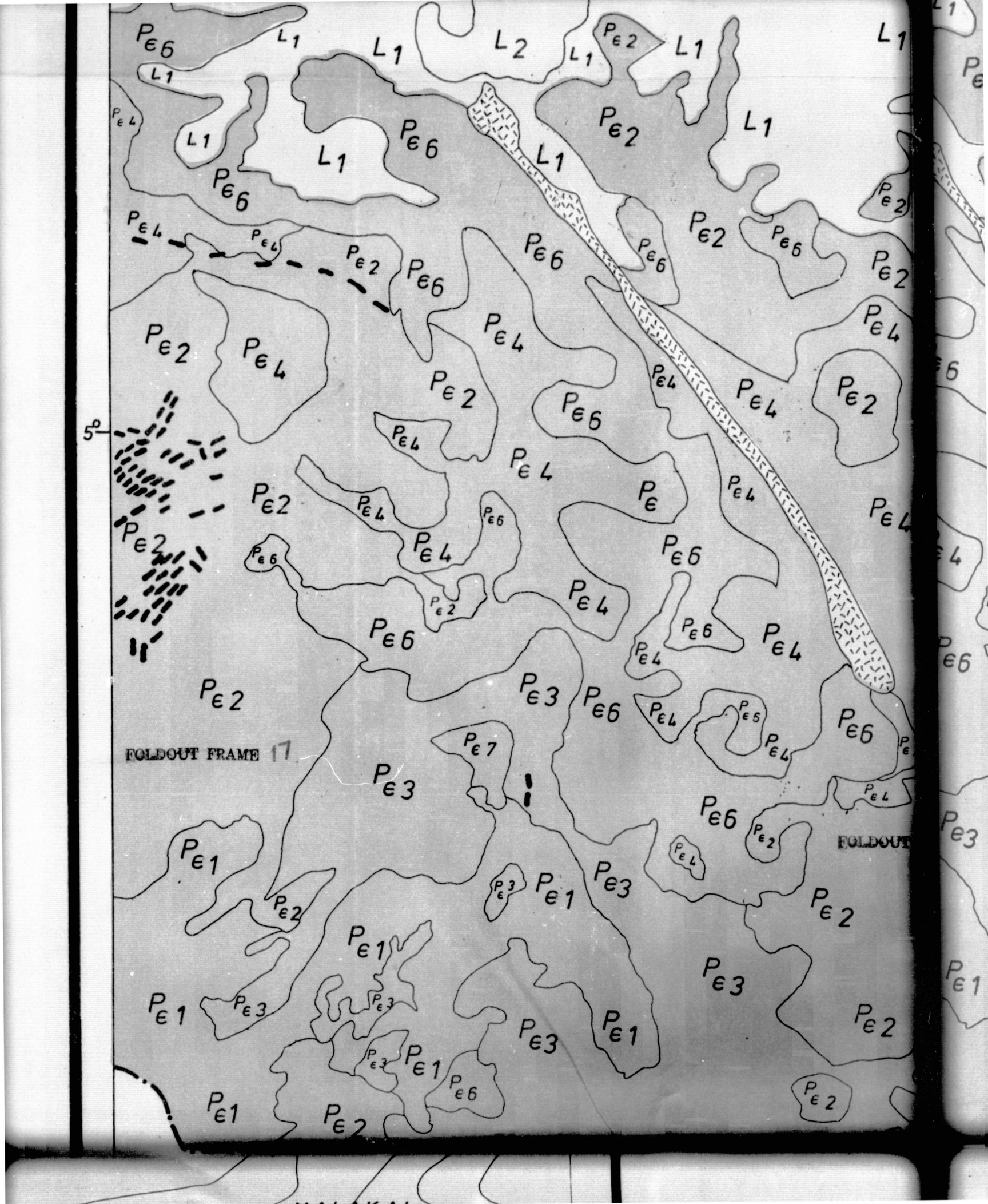
1 CHARNOKITIC AND RELATED ROCKS

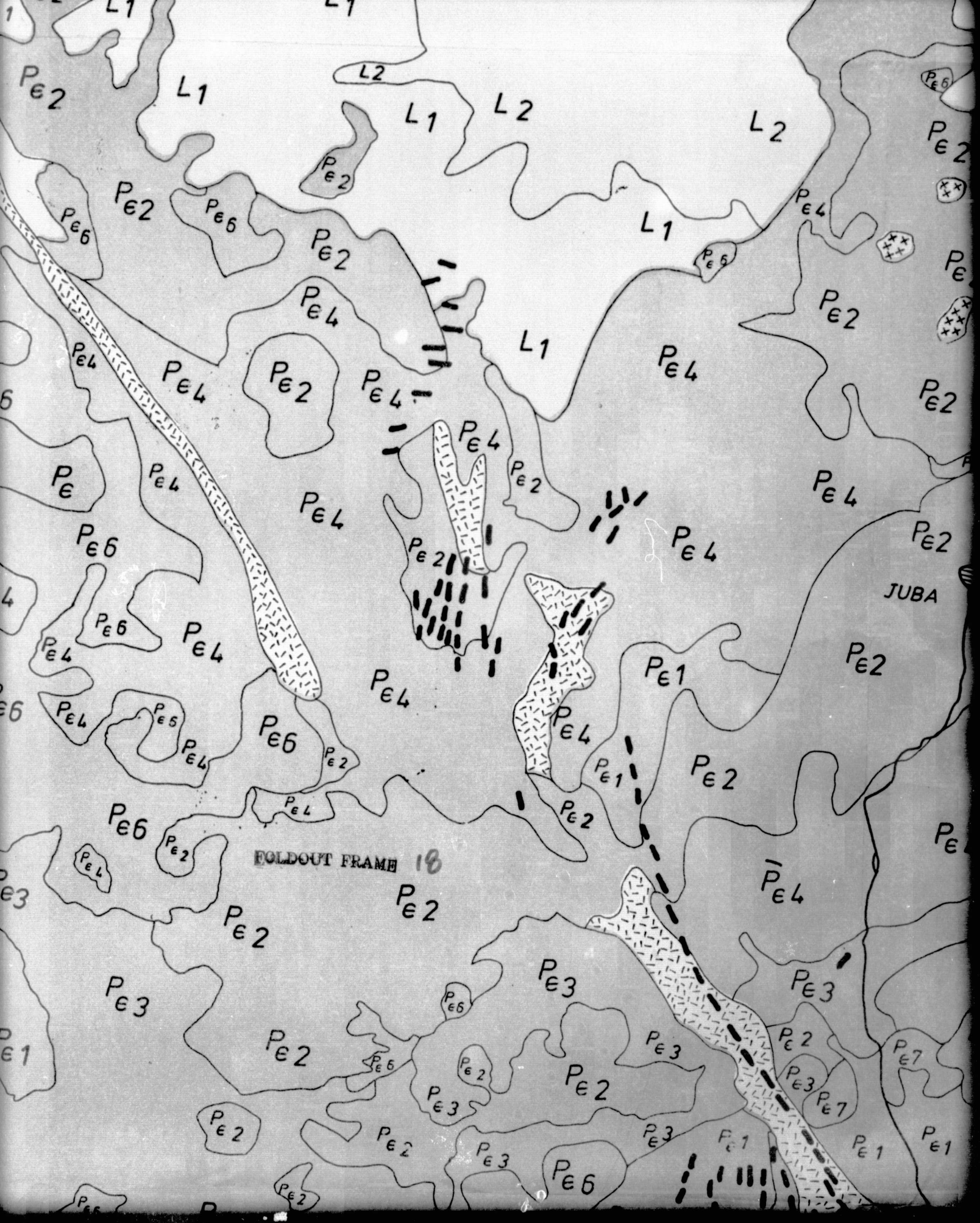
SETTLEMENTS AND SMALL TOWNS

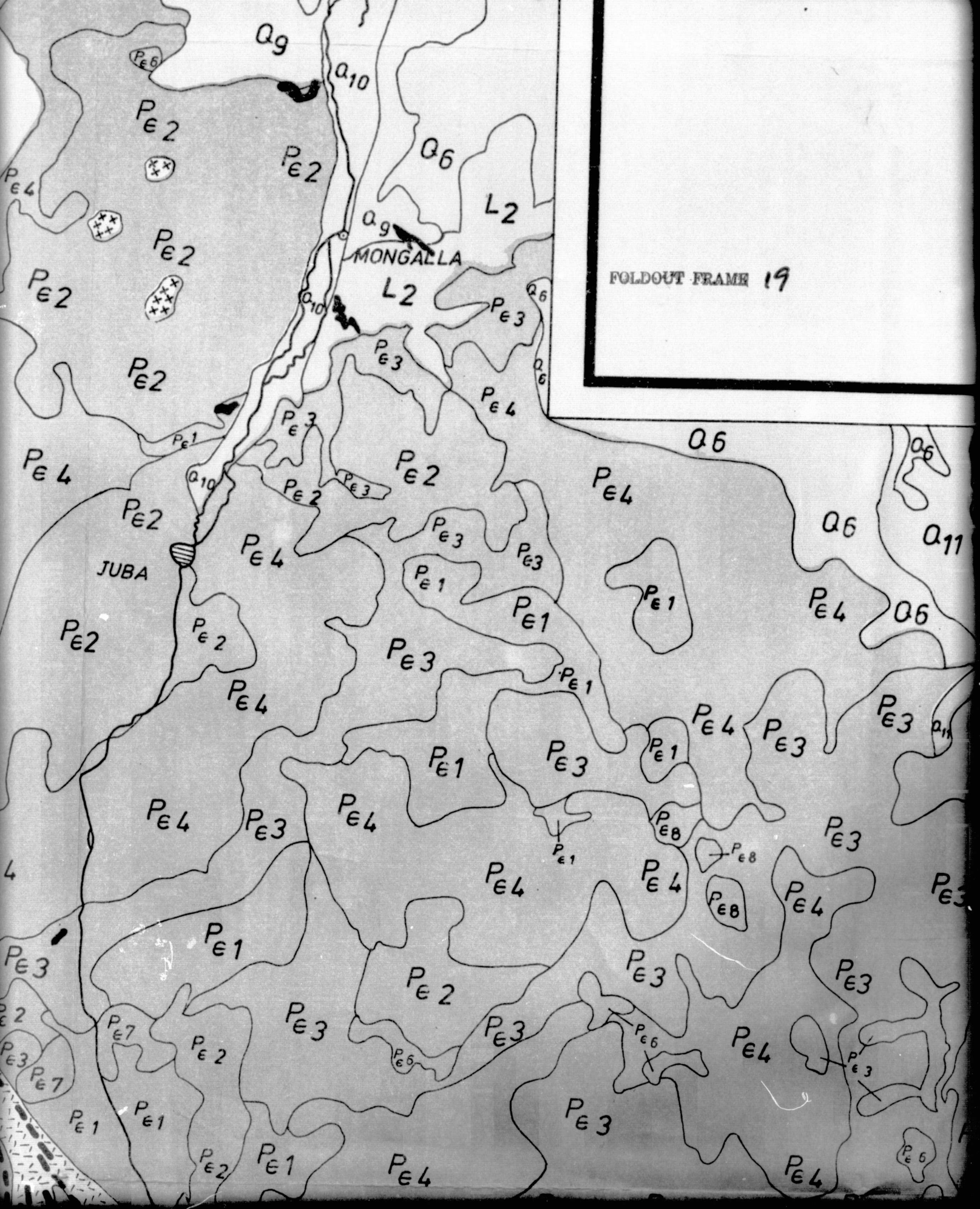
MISSIONARIES

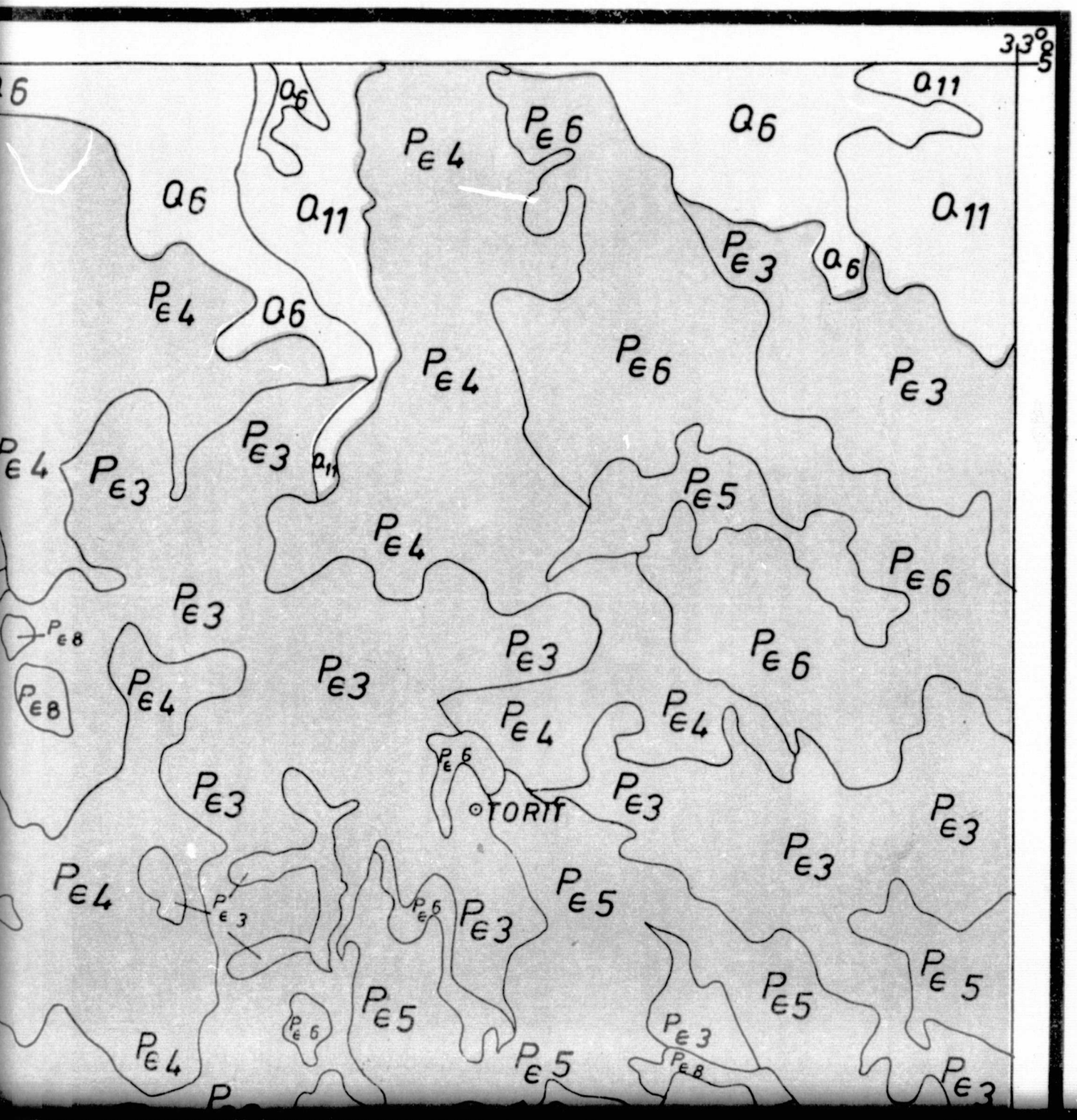
REFERENCE POINT

CITIES AND TOWNS


FOLDOUT FRAME 17
FOLDOUT
5°


JUBA
FOLDOUT FRAME 18
N


FOLDOUT FRAME 19
JUBA
MONGALLA
Q9
Q10
Q6
L2
Q11
Pε1
Pε2
Pε3
Pε4
Pε6
Pε7
Pε8


33° 5
Q6
Q11
PЄ4
PЄ6
PЄ3
PЄ5
PЄ8
TORIT

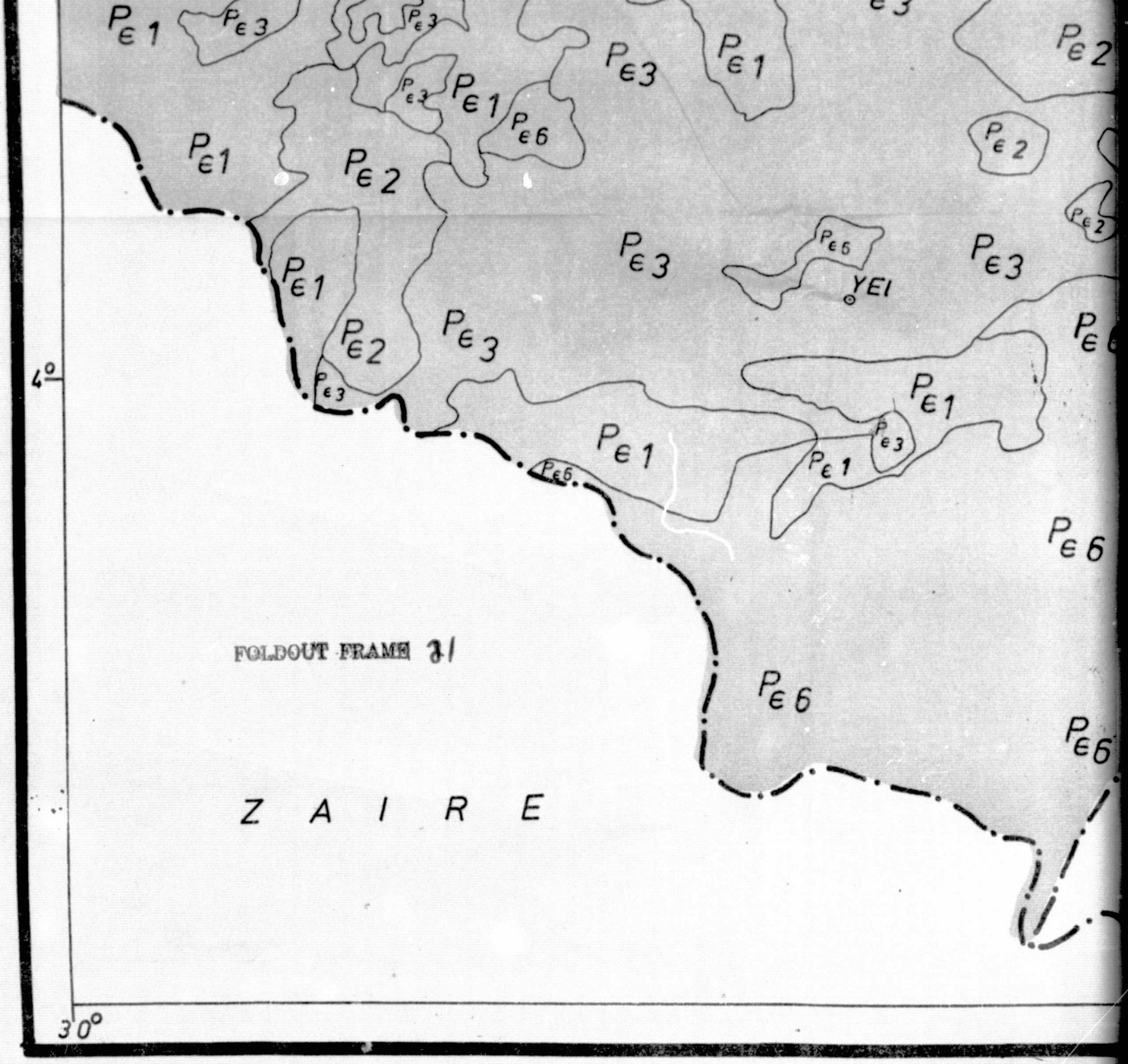
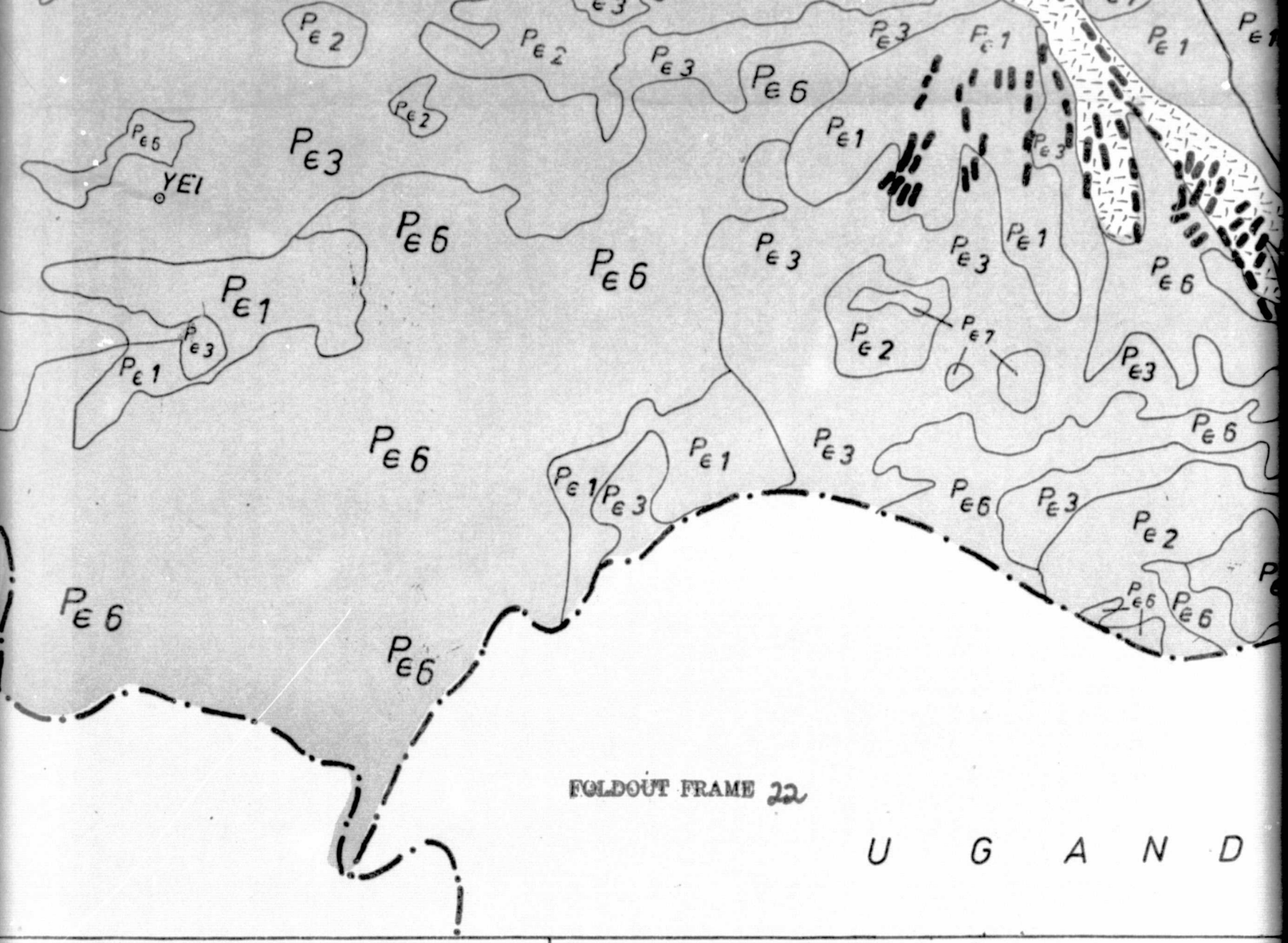


FIG. 5. GEOLOGICAL MA

I F



LOGICAL MAP OF THE JONGLEI CON

(FROM LANDSAT SATELLITE I ATE

10 5 0 10 20 30 40 50



FOLDOUT FRAME 23

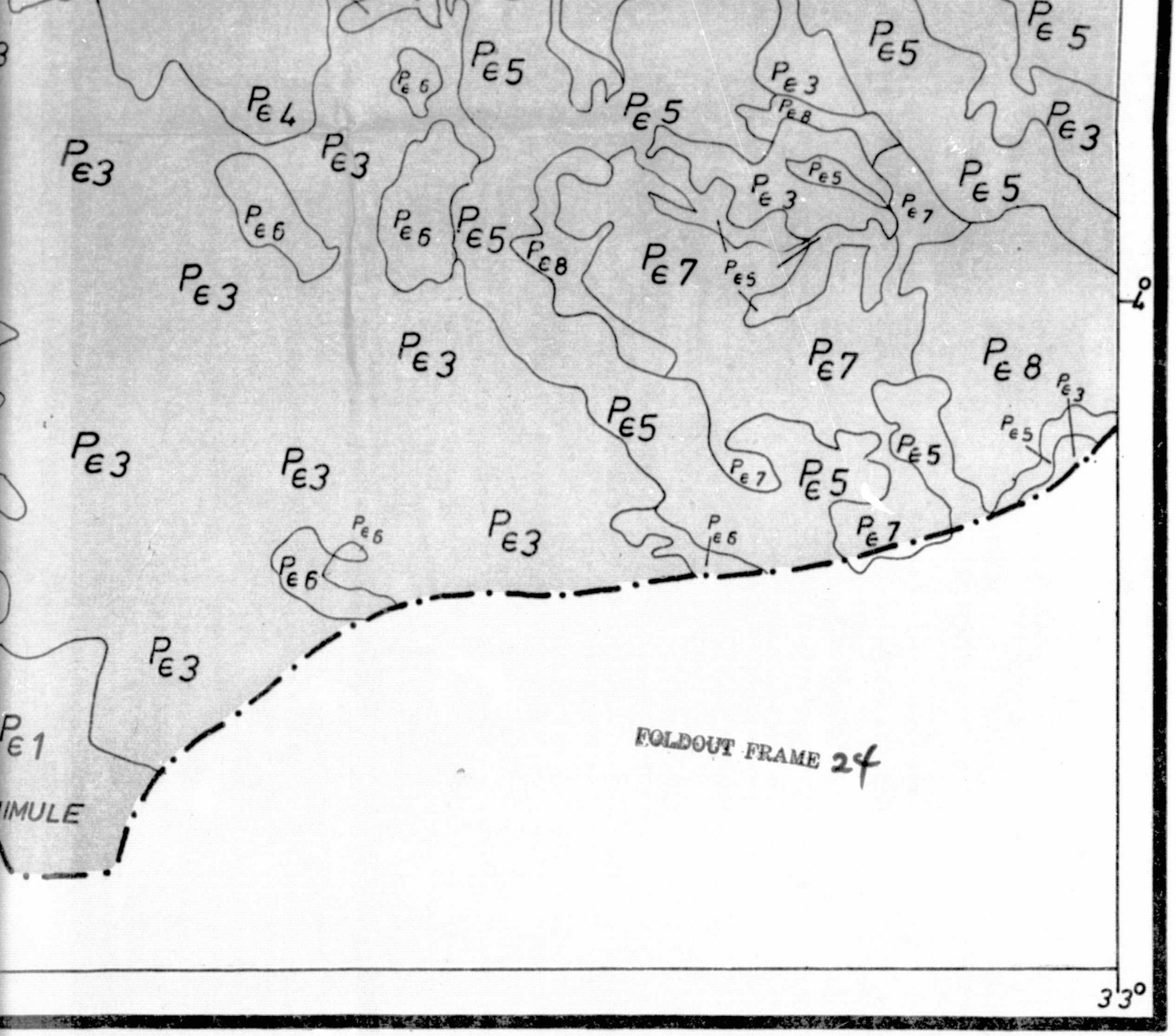
3 2°

ONGLEI CANAL PROJECT AREA, SO T

ATELLITE IMAGES, FEBRUARY 1973)

0 40 50 60 70 80 90 100 Km.

7°



T AREA, SOUTHERN SUDAN

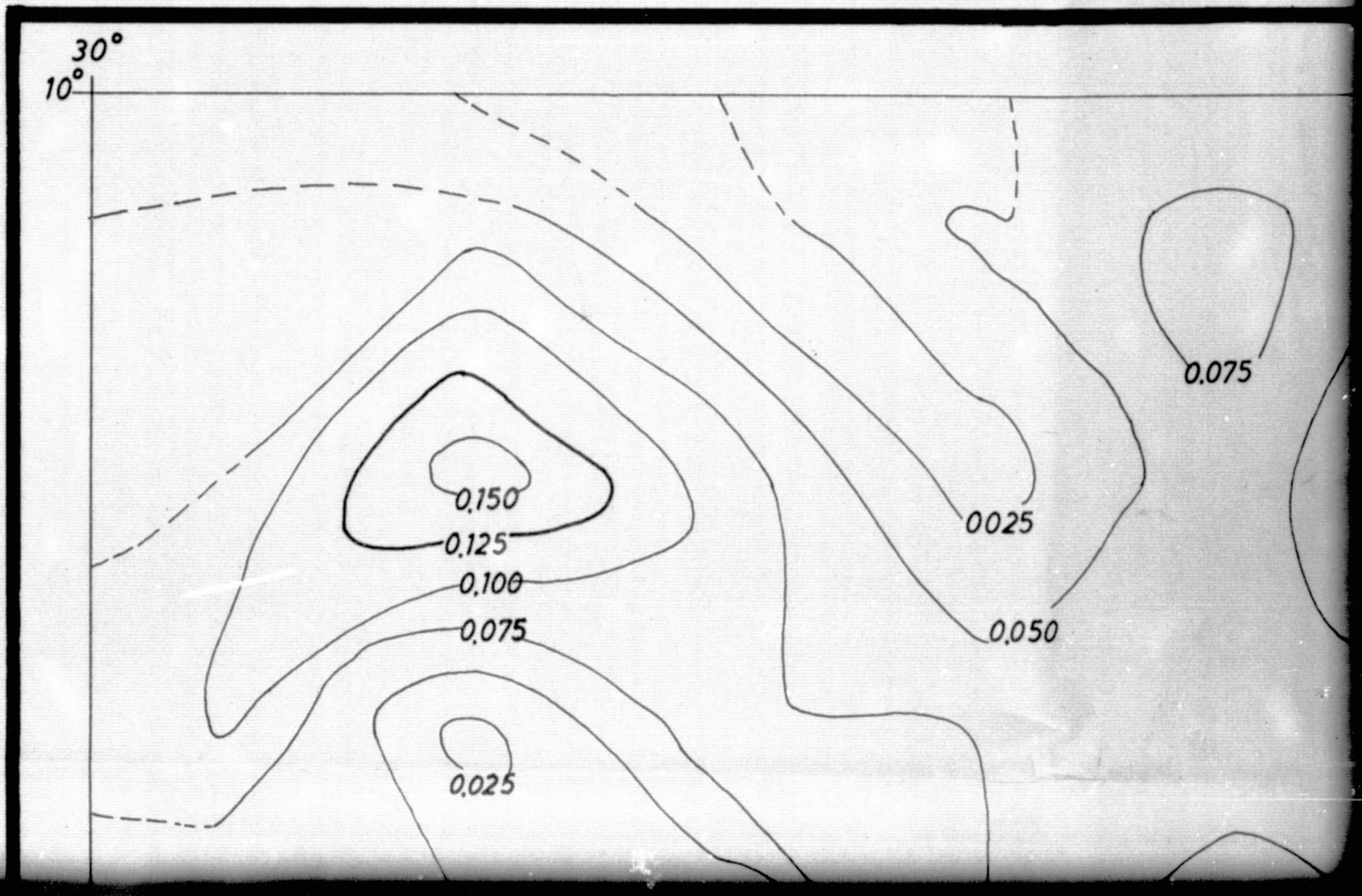
1973)

FOLDOUT FRAME 1

REMOTE SENSING CENTER NG

ACADEMY OF SCIENTIFIC RESEARCH AND TE ESE

CAIRO _ EGYPT EGY

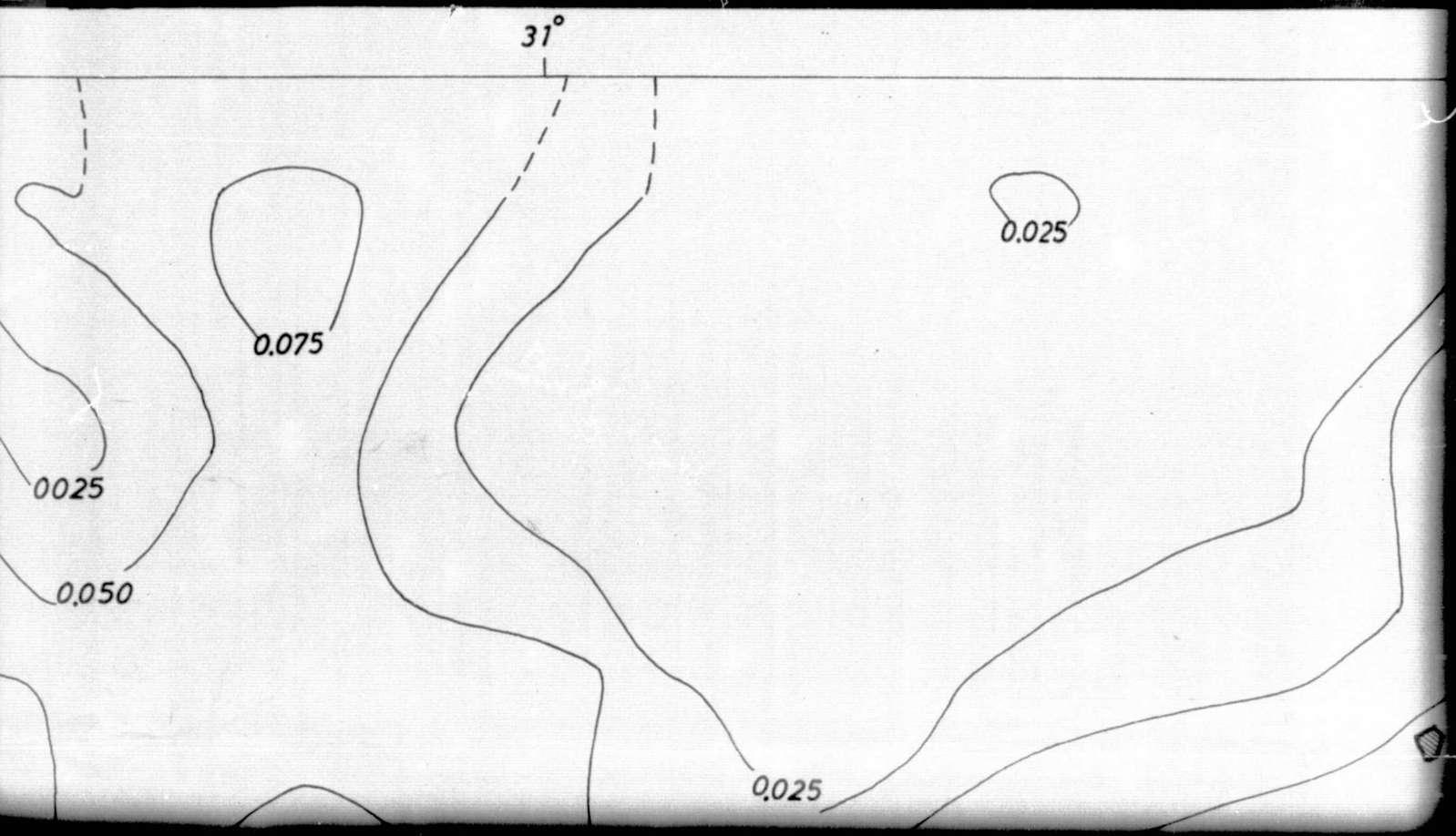


FOLDOUT FRAME 2

G CENTER

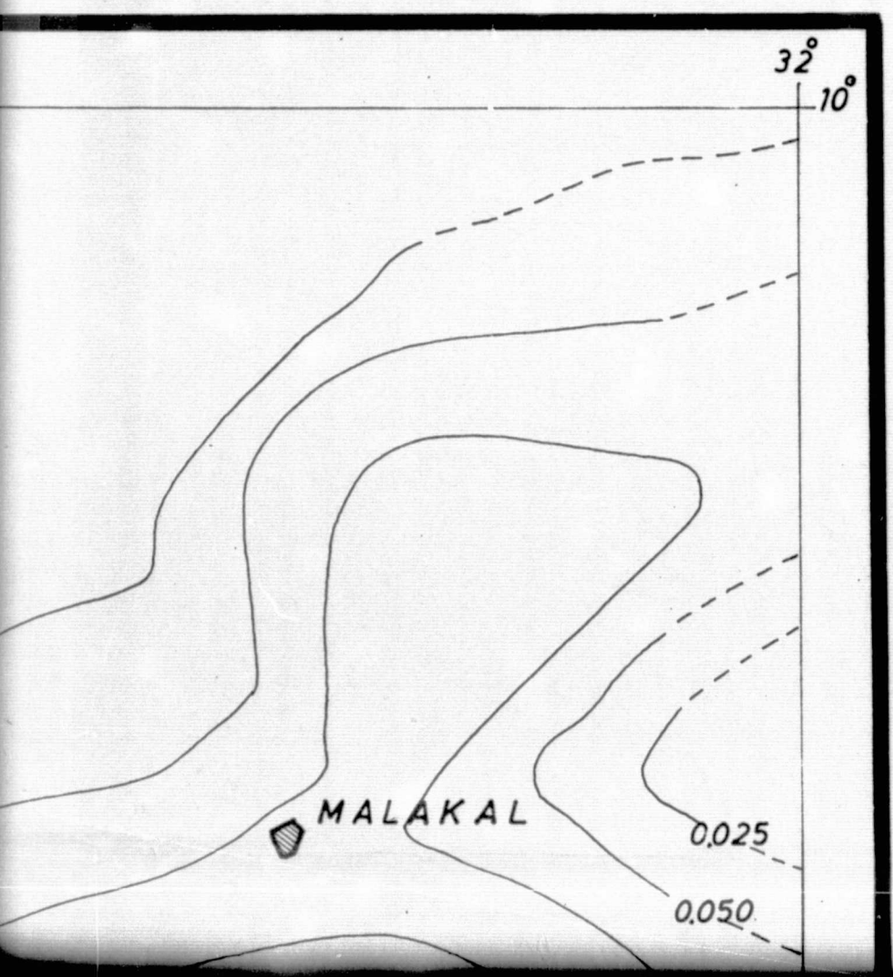
SEARCH AND TECHNOLOGY

GYPT



(N) DISTRIBUTION OF THE STRUCTURAL LINEAMENTS

FOLDOUT FRAME 3



MINISTRY OF IRRIGATION,
ARAB REPUBLIC OF EGYPT

THE PERMANE
COMMISSION

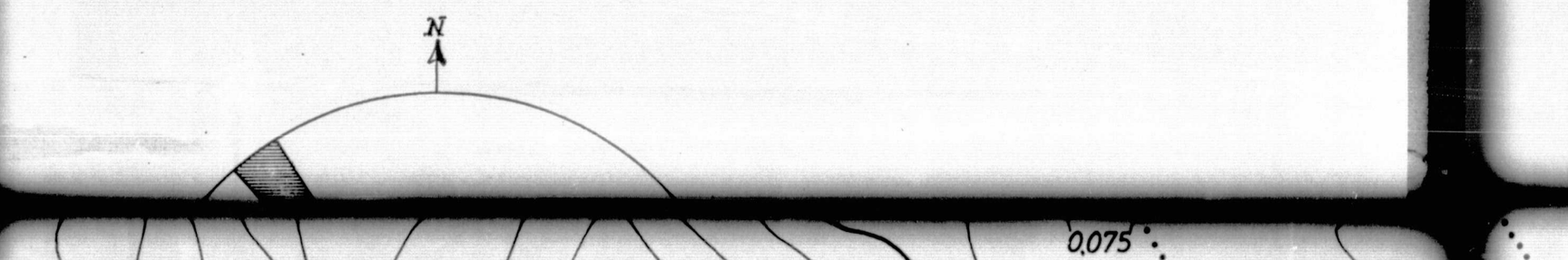
FOLDOUT FRAME 1

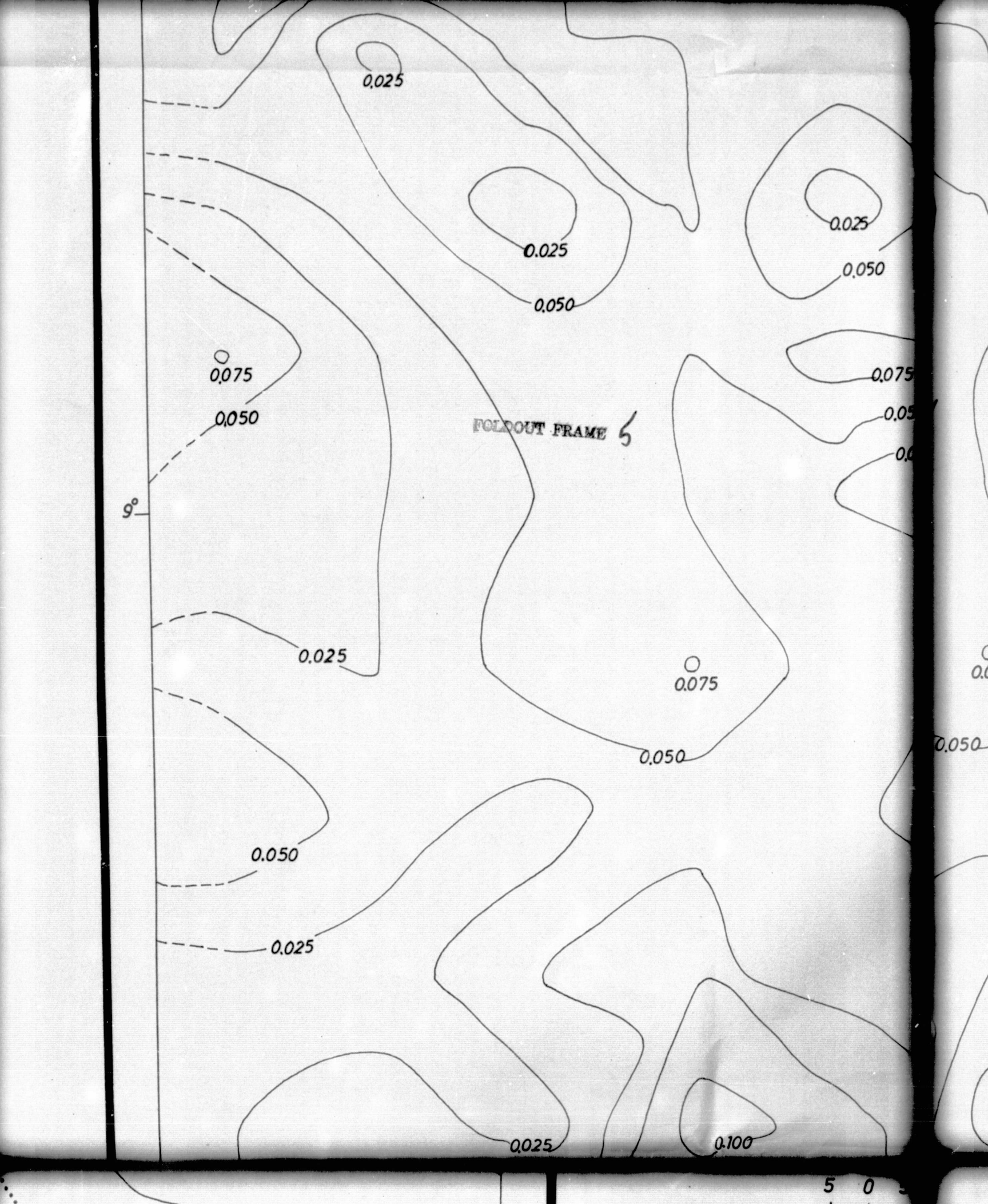
4

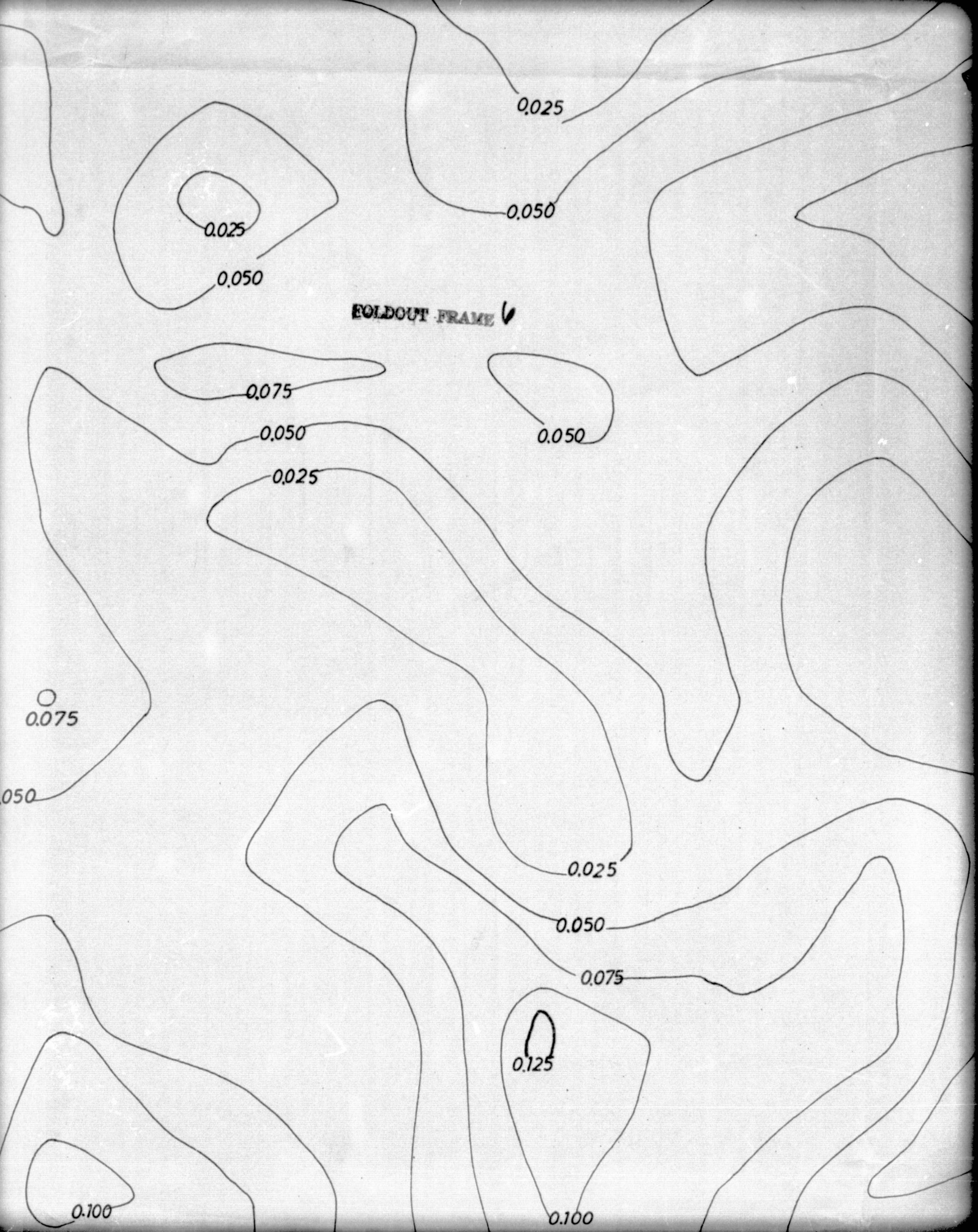
Y OF IRRIGATION,
EPUBLIC OF EGYPT

MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

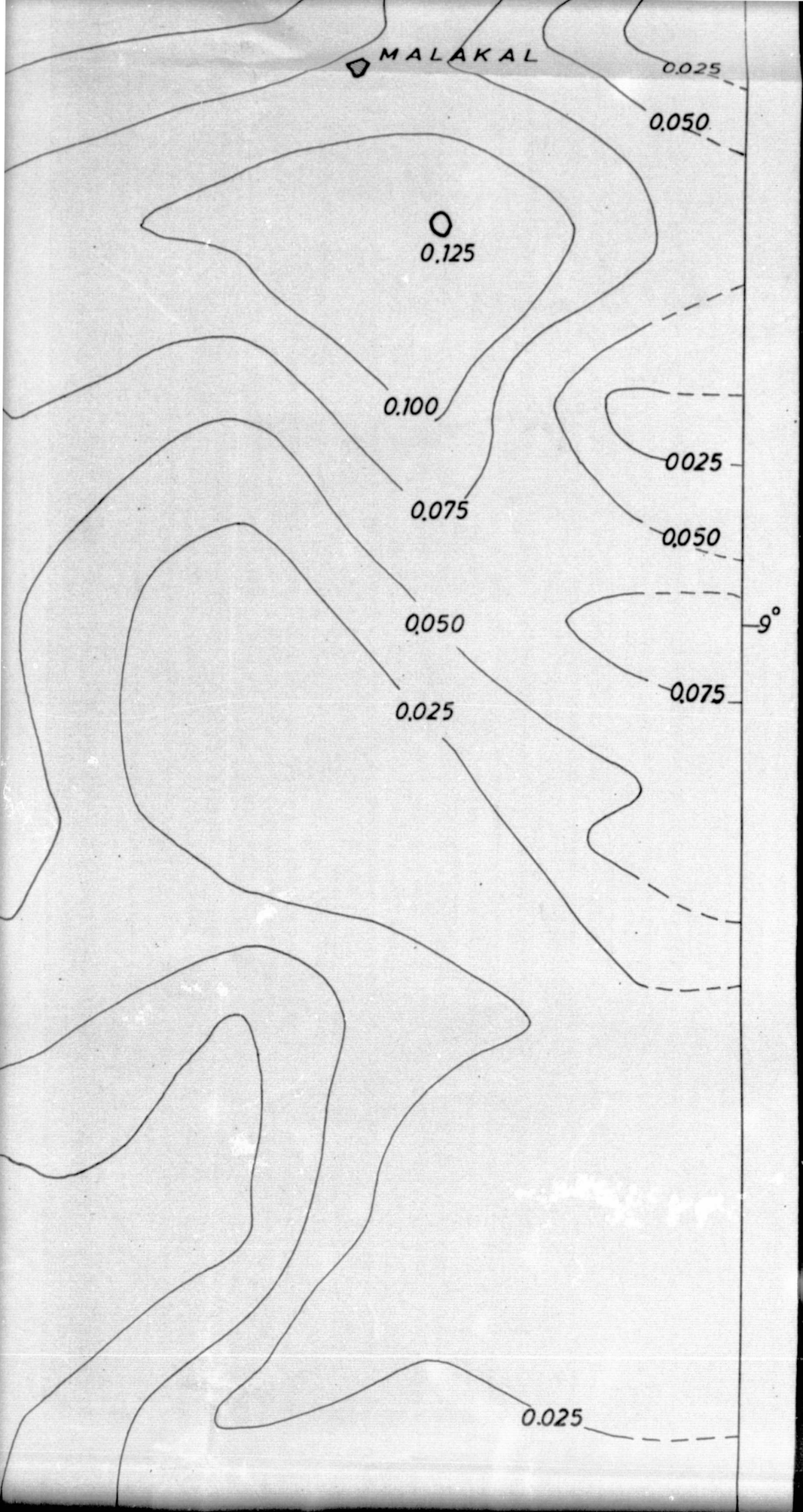
THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS




0.025
0.025
0.050
0.025
0.050
0.075
0.050
FOLDOUT FRAME 5
0.075
0.05
9°
0.025
0.075
0.050
0.050
0.025
0.025
0.100
5 0



5 0 5 10 15 20 25 30 35 Km

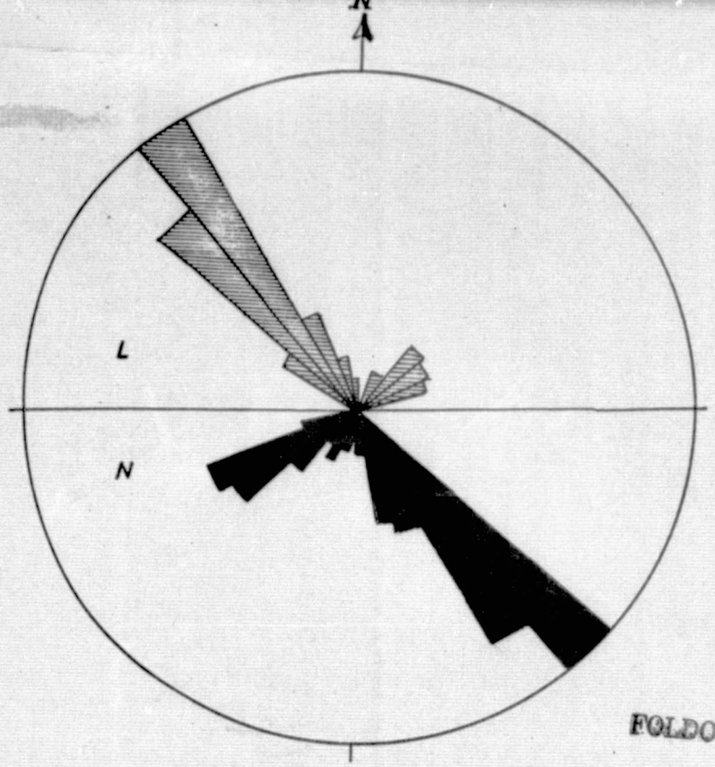


FOLDOUT FRAME 7

7

FIG.4b

FIG.4b. ROSE DIAG
(N) DISTRIE
IN THE NO
JONGLEI C

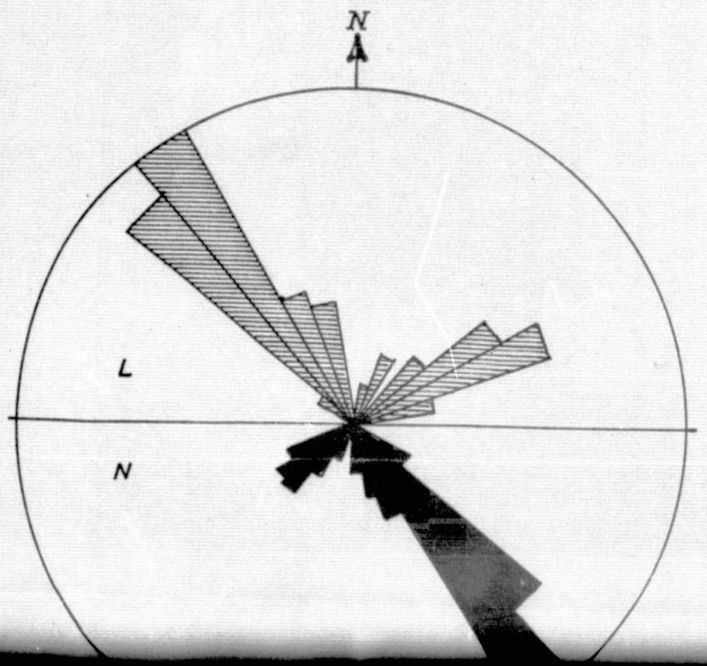


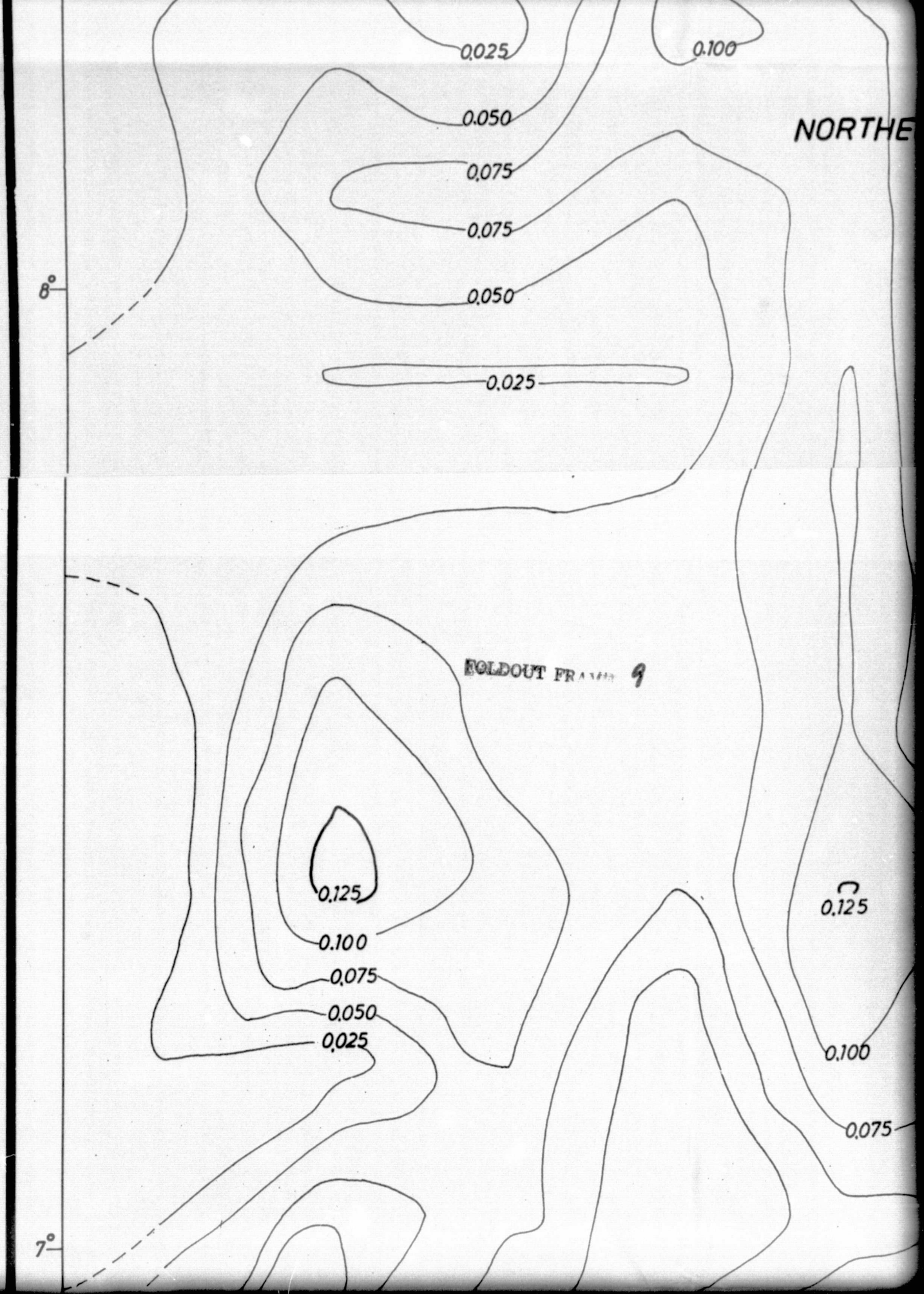
FOLDOUT FRAME 8

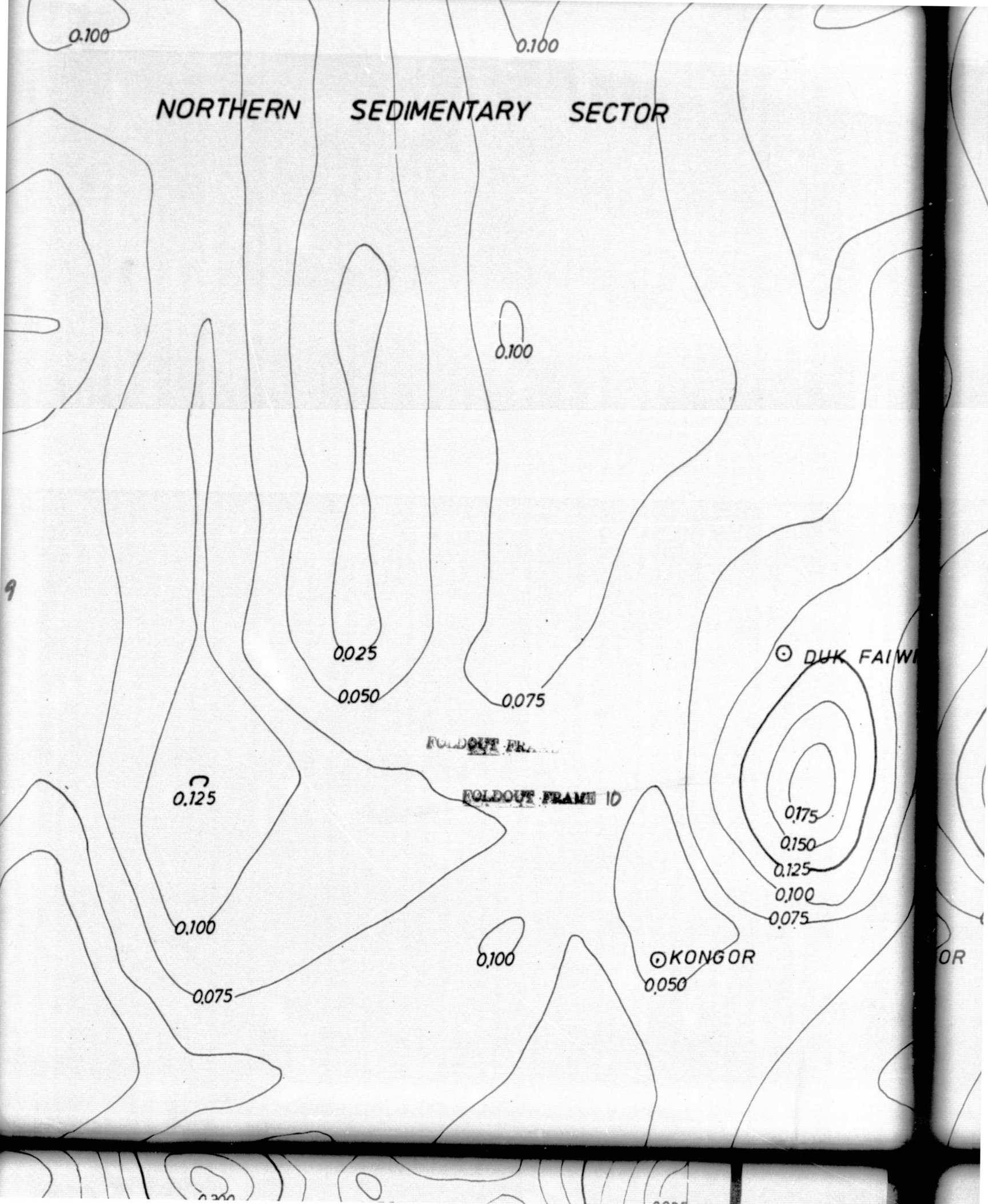
0 500 1000km

0 22 44 Lines

FIG.4b. ROSE DIAGRAM FOR THE LENGTH (L) AND NUMBER (N) DISTRIBUTION OF THE STRUCTURAL LINEAMENTS IN THE NORTHERN SEDIMENTARY SECTOR OF THE JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN.




0.025
0.100
0.050
NORTHE
0.075
0.075
8°
0.050
0.025
FOLDOUT FRAME 9
9
0.125
0.125
0.100
0.075
0.050
0.100
0.025
0.075
7°


NORTHERN SEDIMENTARY SECTOR
0.100
0.100
0.100
0.025
0.050
0.075
0.125
0.100
0.075
0.100
0.050
0.175
0.150
0.125
0.100
0.075
DUK FAIWI
KONGOR
FOLDOUT FRAME 10

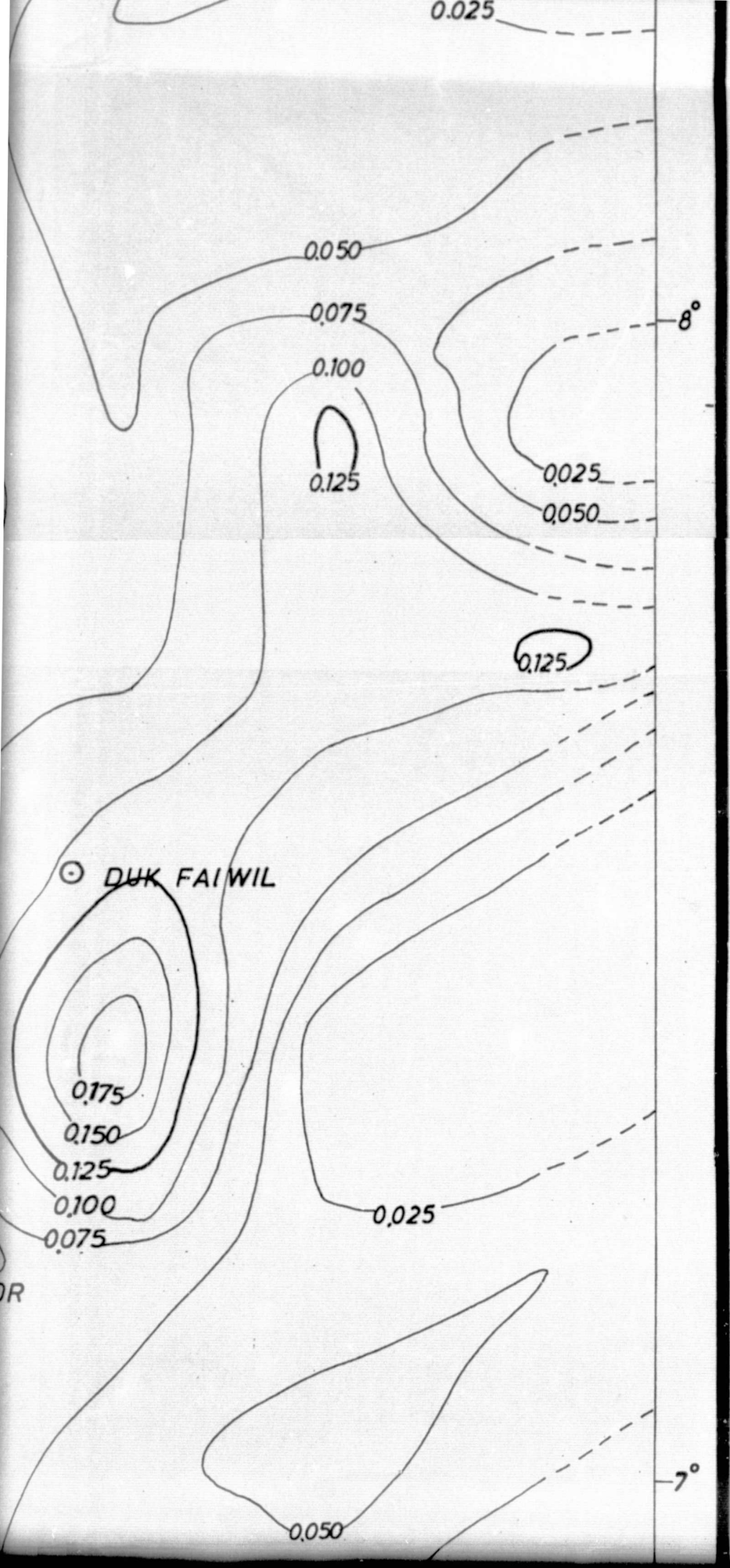


FIG 4c ROSE DIAGRAM FOR
DISTRIBUTION OF THE
THE SOUTHERN BASE
CANAL PROJECT AREA

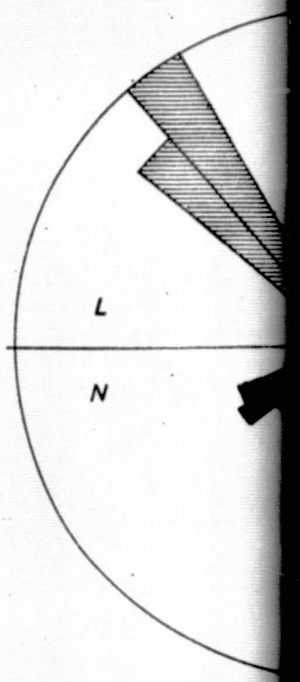


FIG. 4d. ROSE DIAGRAM
(N) DISTRIBUTION
IN JONGLEI CANA

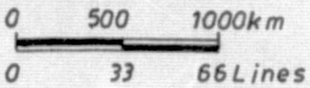
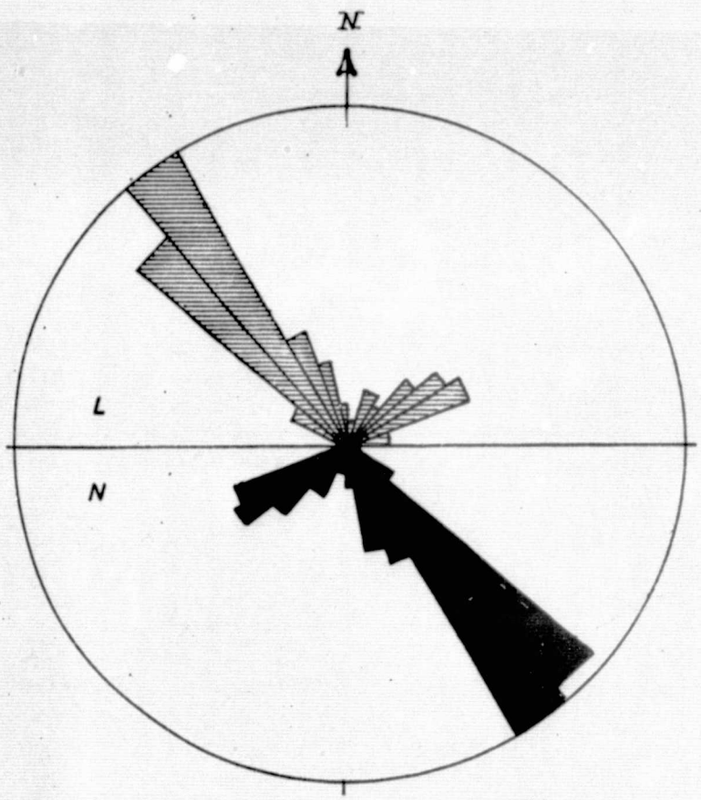


FIG 4c ROSE DIAGRAM FOR THE LENGTH (L) AND NUMBER (N) DISTRIBUTION OF THE STRUCTURAL LINEAMENTS IN THE SOUTHERN BASEMENT SECTOR OF THE JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN.

RAME 11



BOLDOUT FRAME 12

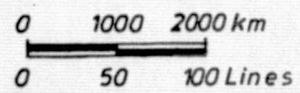
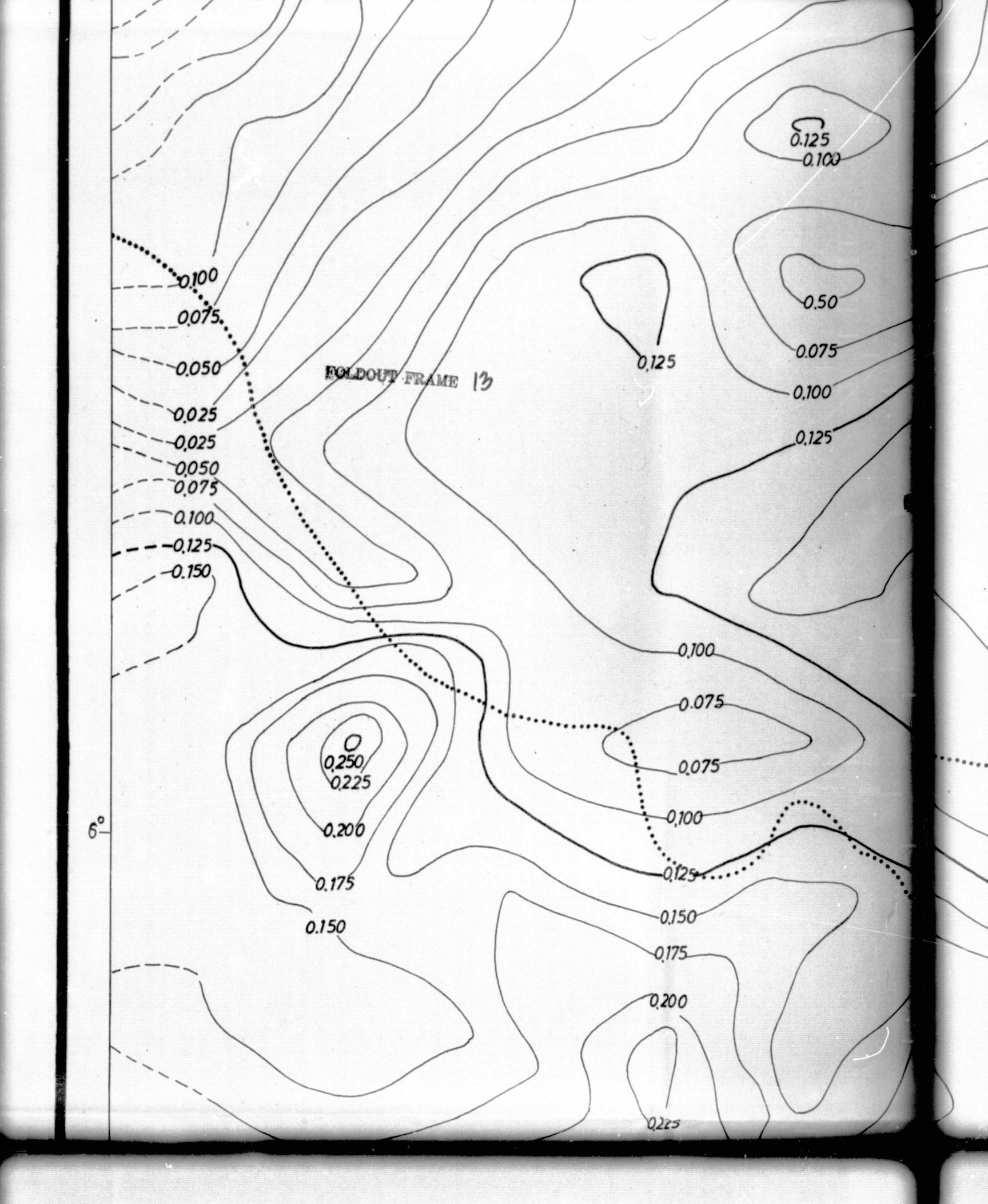
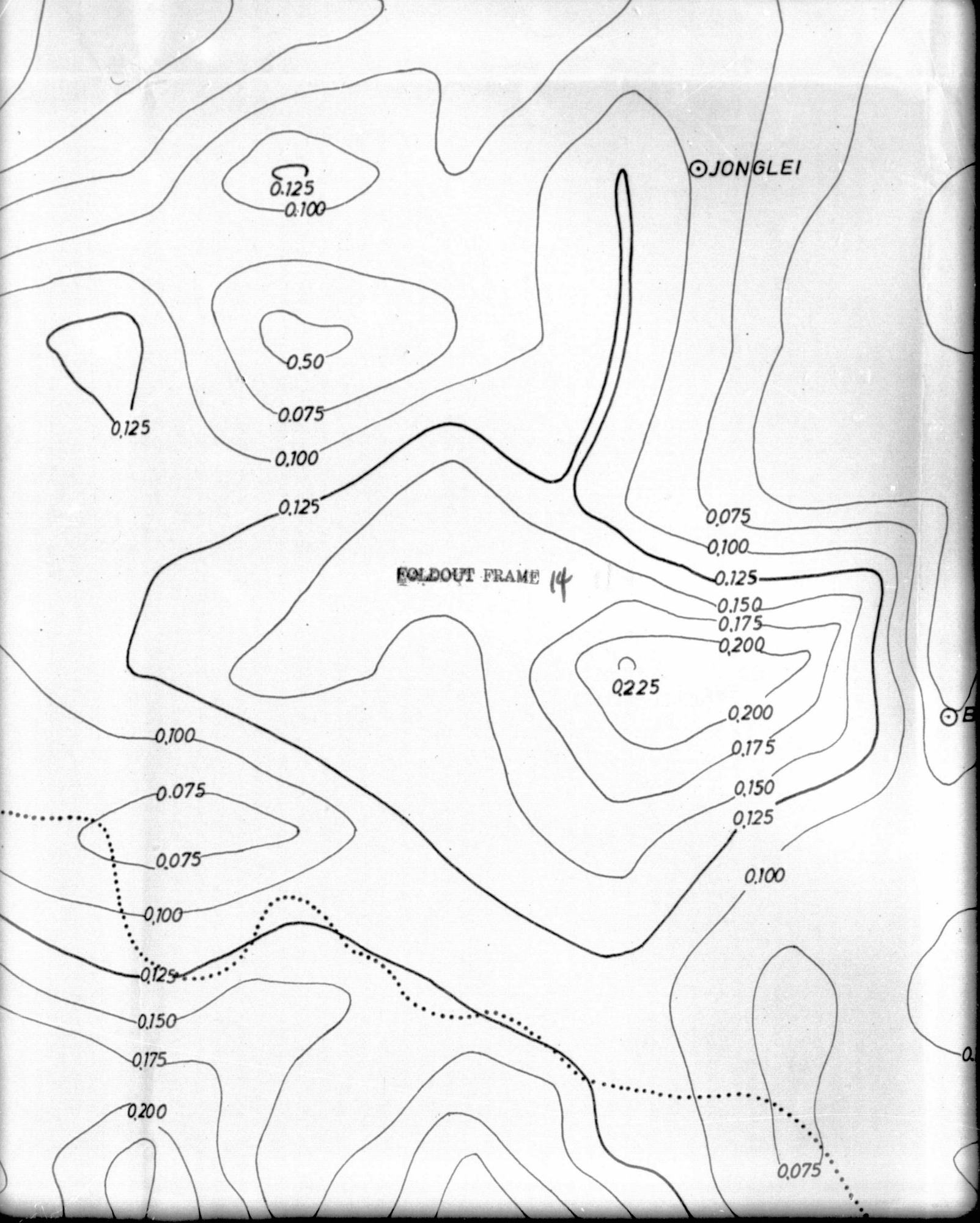
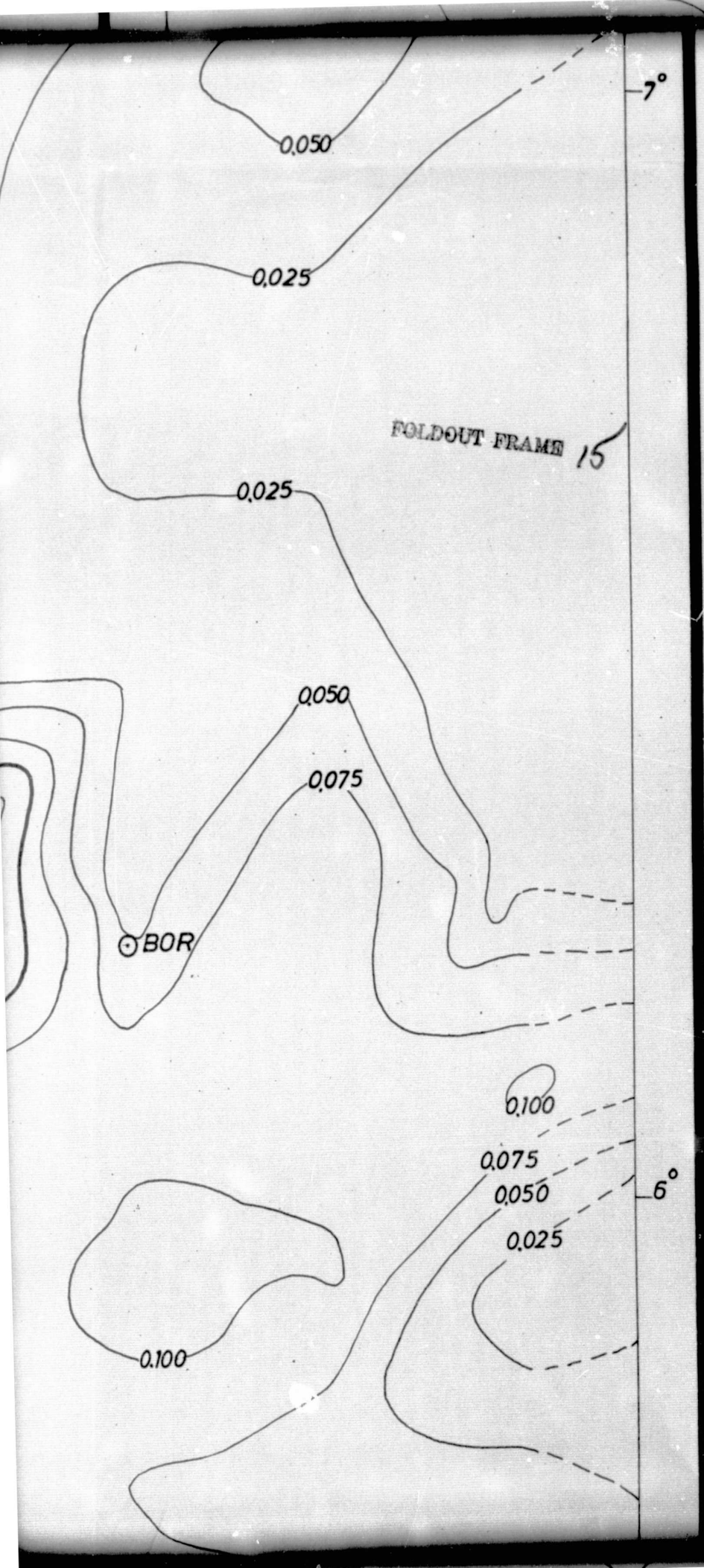


FIG. 4d. ROSE DIAGRAM FOR THE LENGTH (L) AND NUMBER (N) DISTRIBUTION OF THE STRUCTURAL LINEAMENTS IN JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN.


0.125
0.100
0.100
0.075
0.050
0.025
0.025
0.050
0.075
0.100
0.125
0.150
0.50
0.075
0.100
0.125
FOLDOUT FRAME 13
0.125
0.100
0.075
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.225
0.200
0.150
0.150
0.175
0.200
0.225
6°


⊙JONGLEI
0.125
0.100
0.50
0.075
0.100
0.125
0.125
0.075
0.100
0.125
0.150
0.175
0.200
0.225
0.200
0.175
0.150
0.125
0.100
FOLDOUT FRAME 14
0.100
0.075
0.075
0.100
0.125
0.150
0.175
0.200
0.075



FOLDOUT FRAME 15

FIG. 4d. ROSE DIAGRAM
(N) DISTRIBUTIO
IN JONGLEI CA

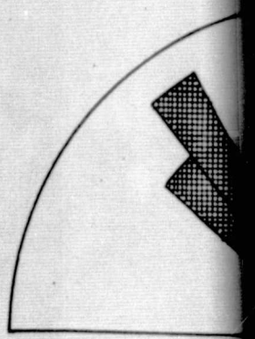
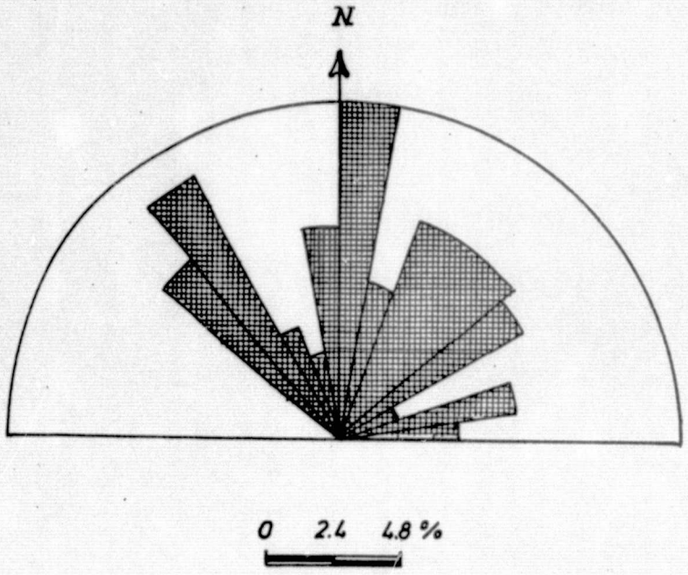


FIG. 4

FIG. 4e. ROSE DIAGRAM FO
THE DELINEATED
CANAL PROJECT A

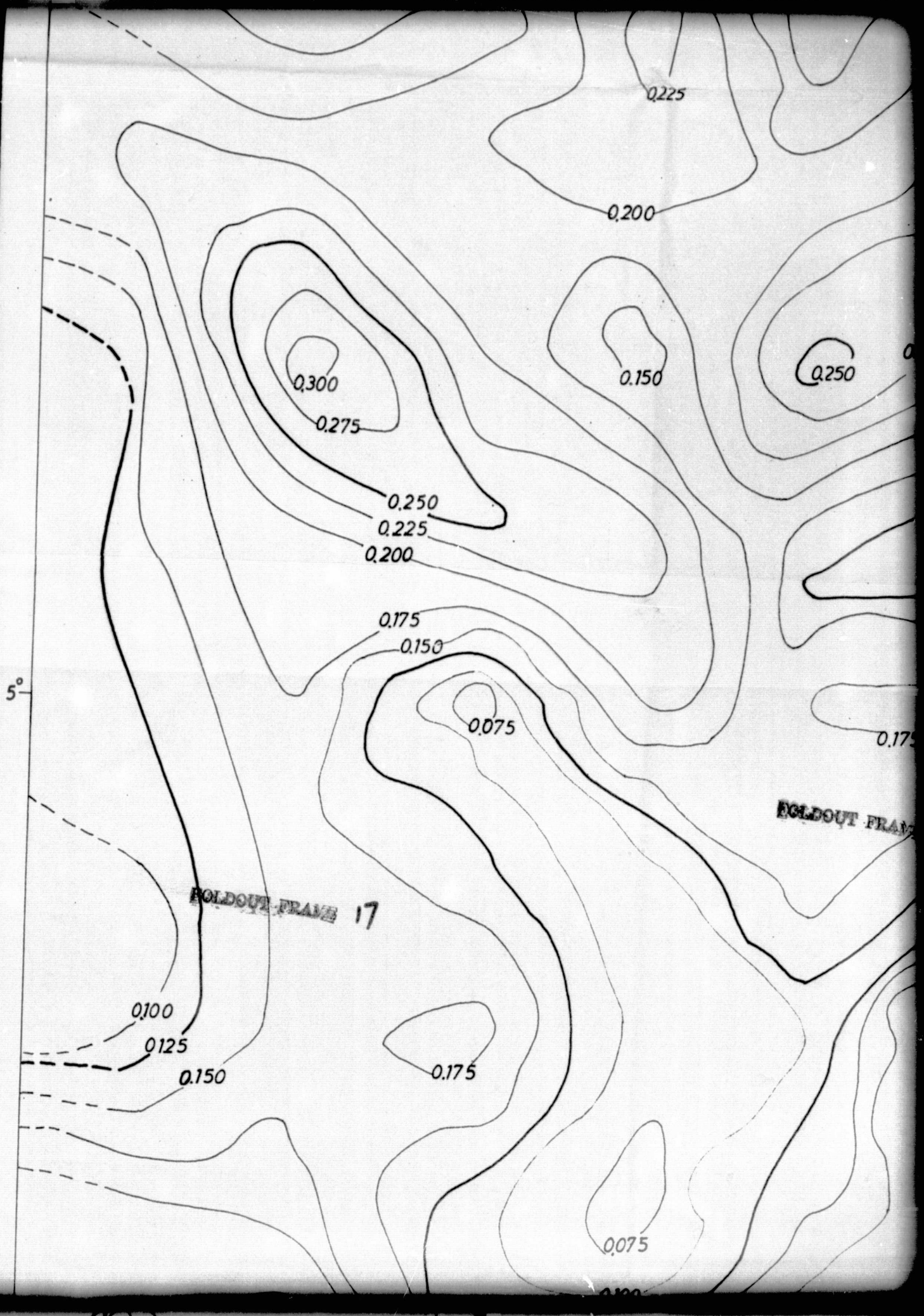
(N) DISTRIBUTION OF THE STRUCTURAL LINEAMENTS IN JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN.

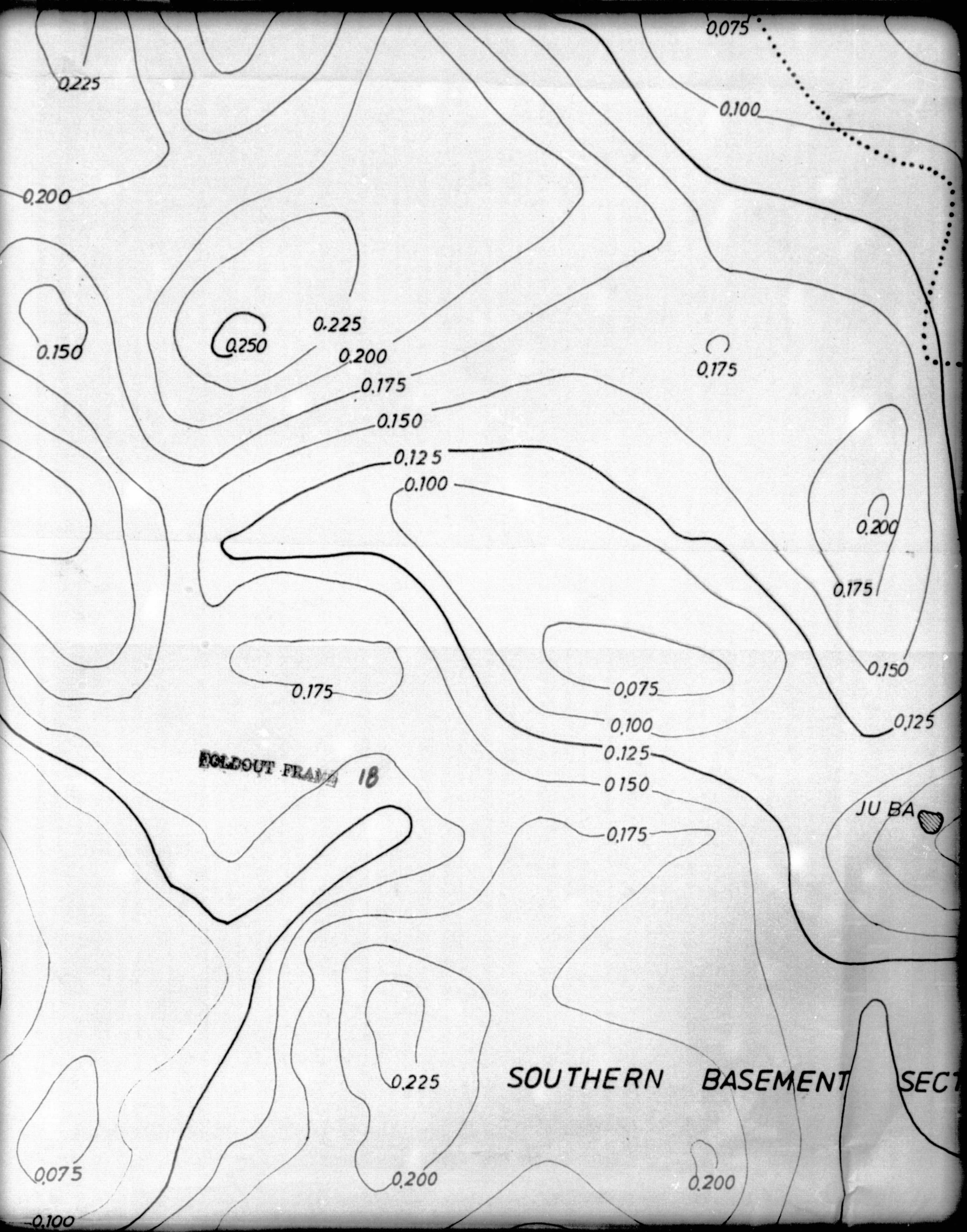


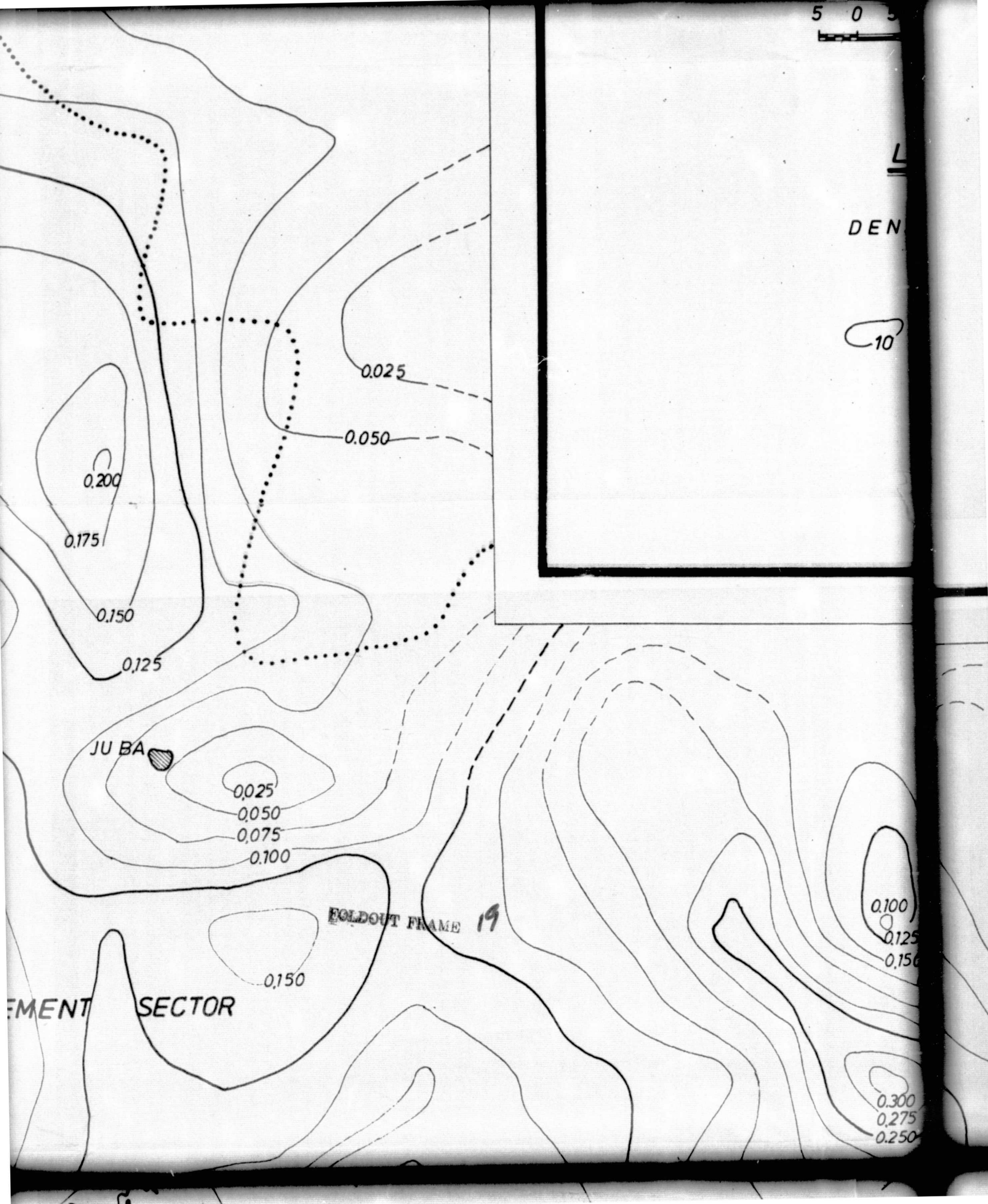
FOLDOUT FRAME 16

FIG. 4e. ROSE DIAGRAM FOR 90 FOLD AXES TRENDS OF THE DELINEATED FOLD TRACES IN JONGLEI CANAL PROJECT AREA, SOUTHERN SUDAN.

5 0 5 10 15 20 25 30 35 Km


0.225
0.200
0.300
0.275
0.150
0.250
0.250
0.225
0.200
0.175
0.150
5°
0.075
FOLDOUT FRAME 17
0.100
0.125
0.150
0.175
0.075


0.075
0.225
0.100
0.200
0.150
0.250
0.225
0.200
0.175
0.175
0.150
0.125
0.100
0.200
0.175
0.150
0.175
0.075
0.100
0.125
0.125
0.150
FOLDOUT FRAME 18
JU BA
0.175
SOUTHERN BASEMENT
0.225
0.075
0.200
0.200
0.100



FOLDOUT FRAME 19

5 0 5 10 15 20 25 30 35 Km

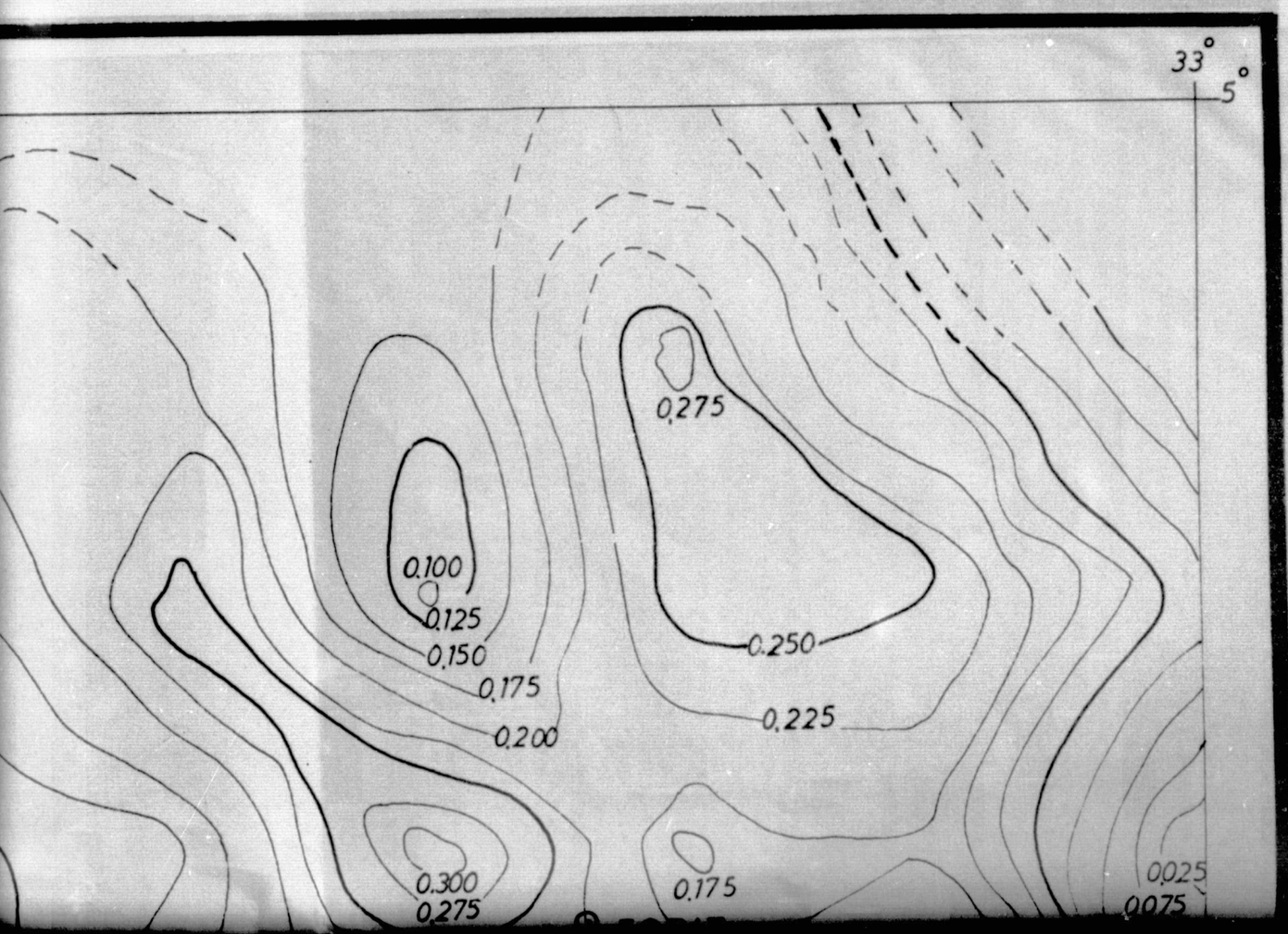
LEGEND

DENSITY OF LINEAMENT

(Km / Km^2)

10 CONTOUR LINE

FOLDOUT FRAME 20



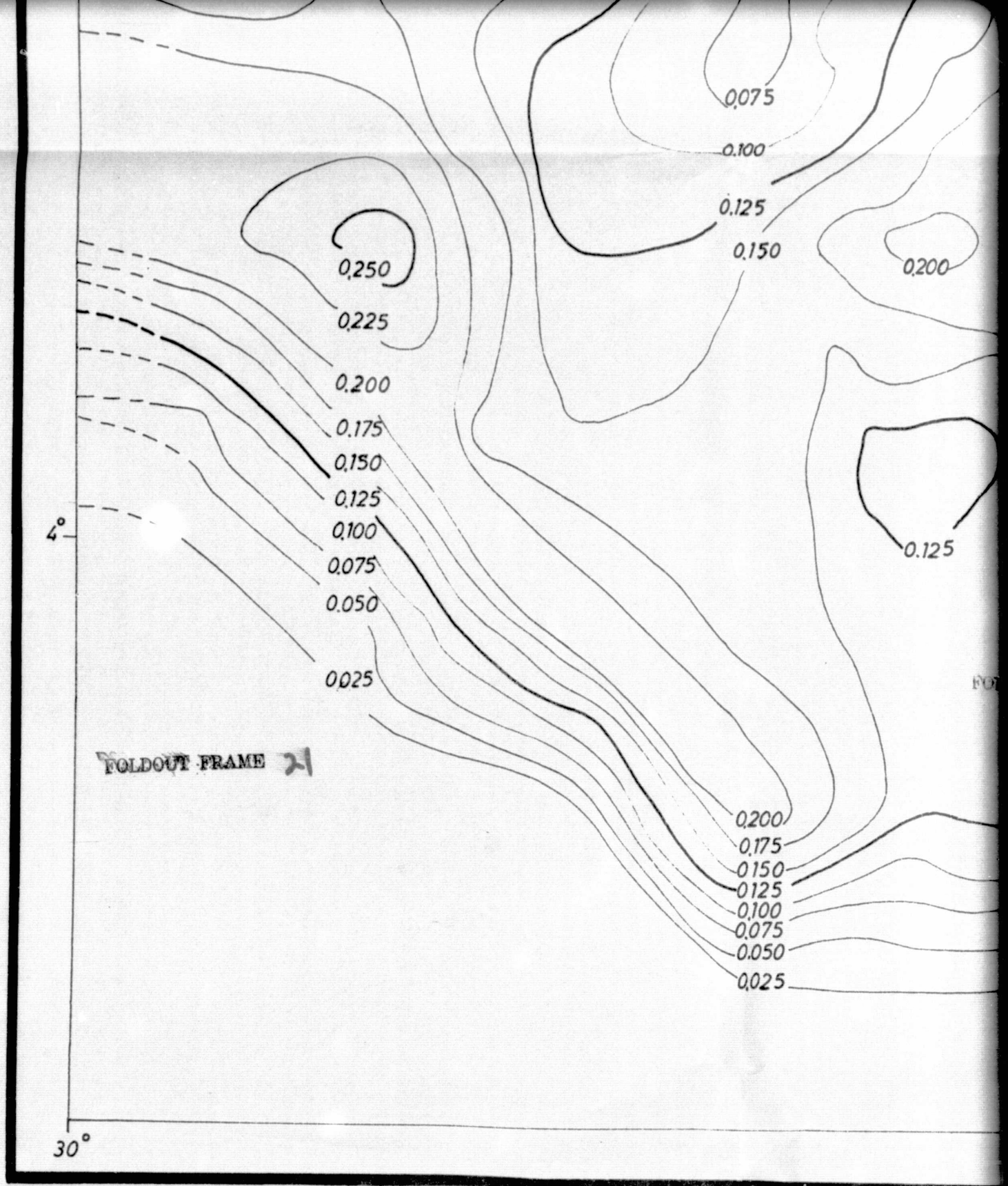
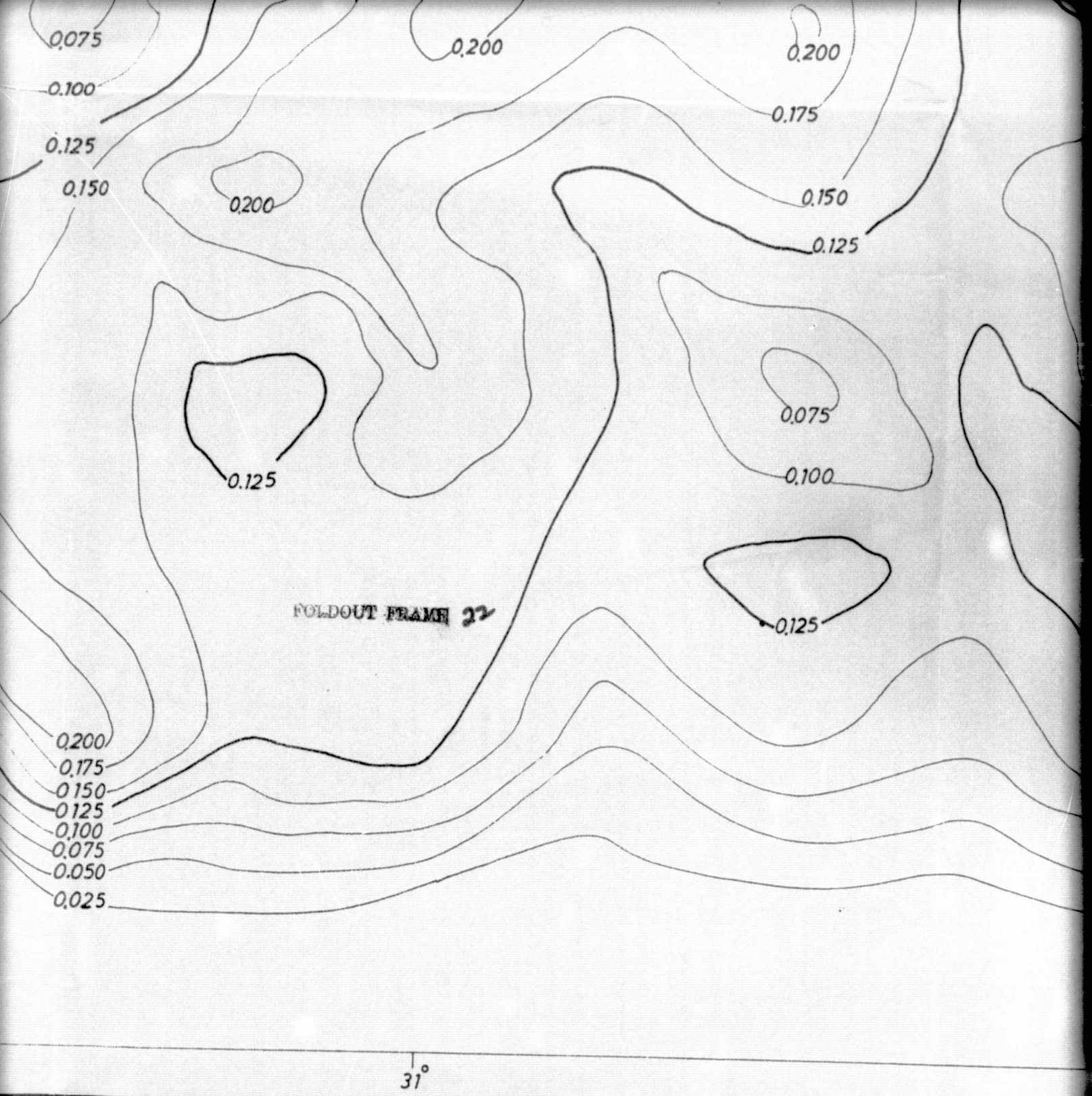
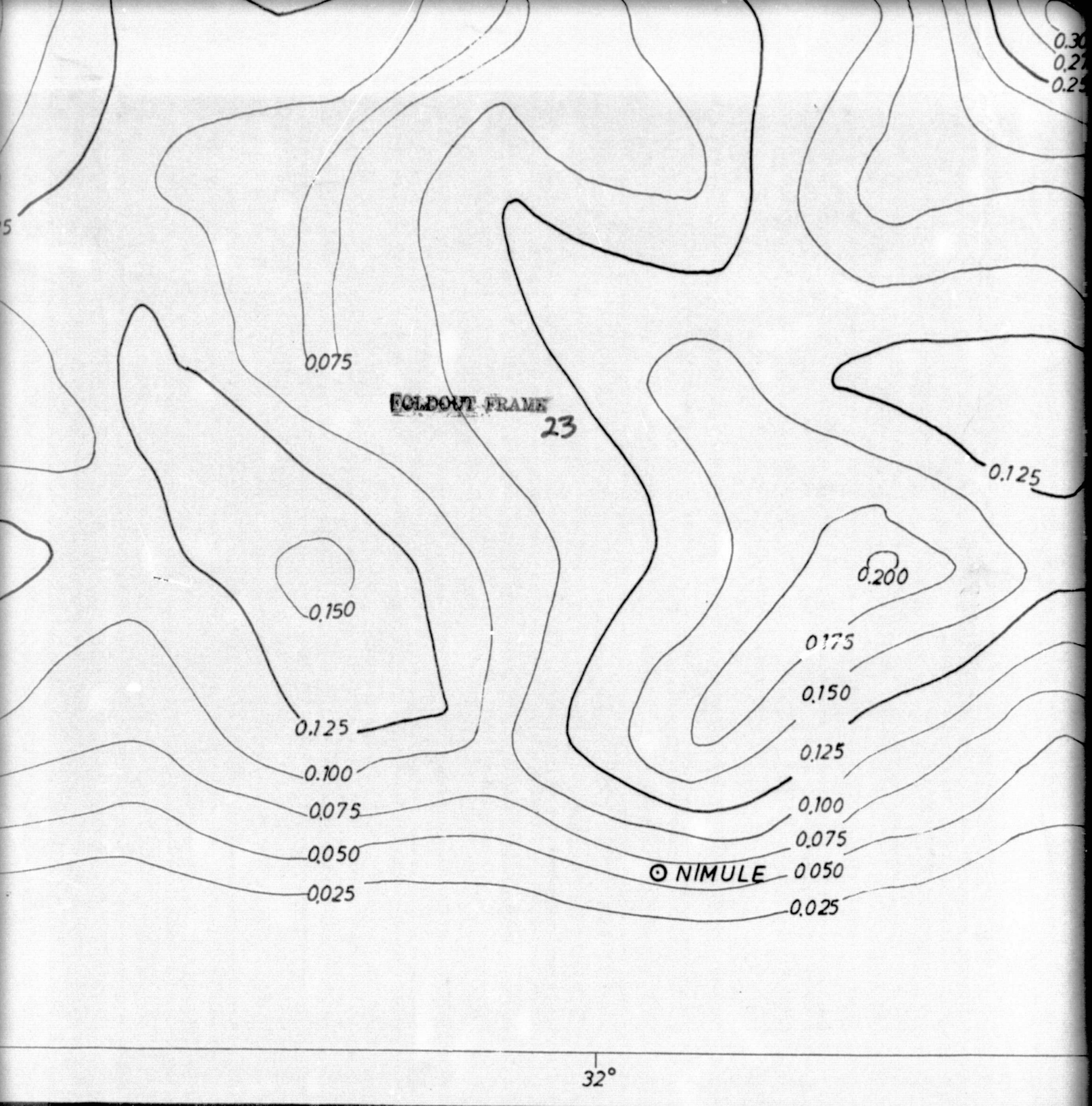


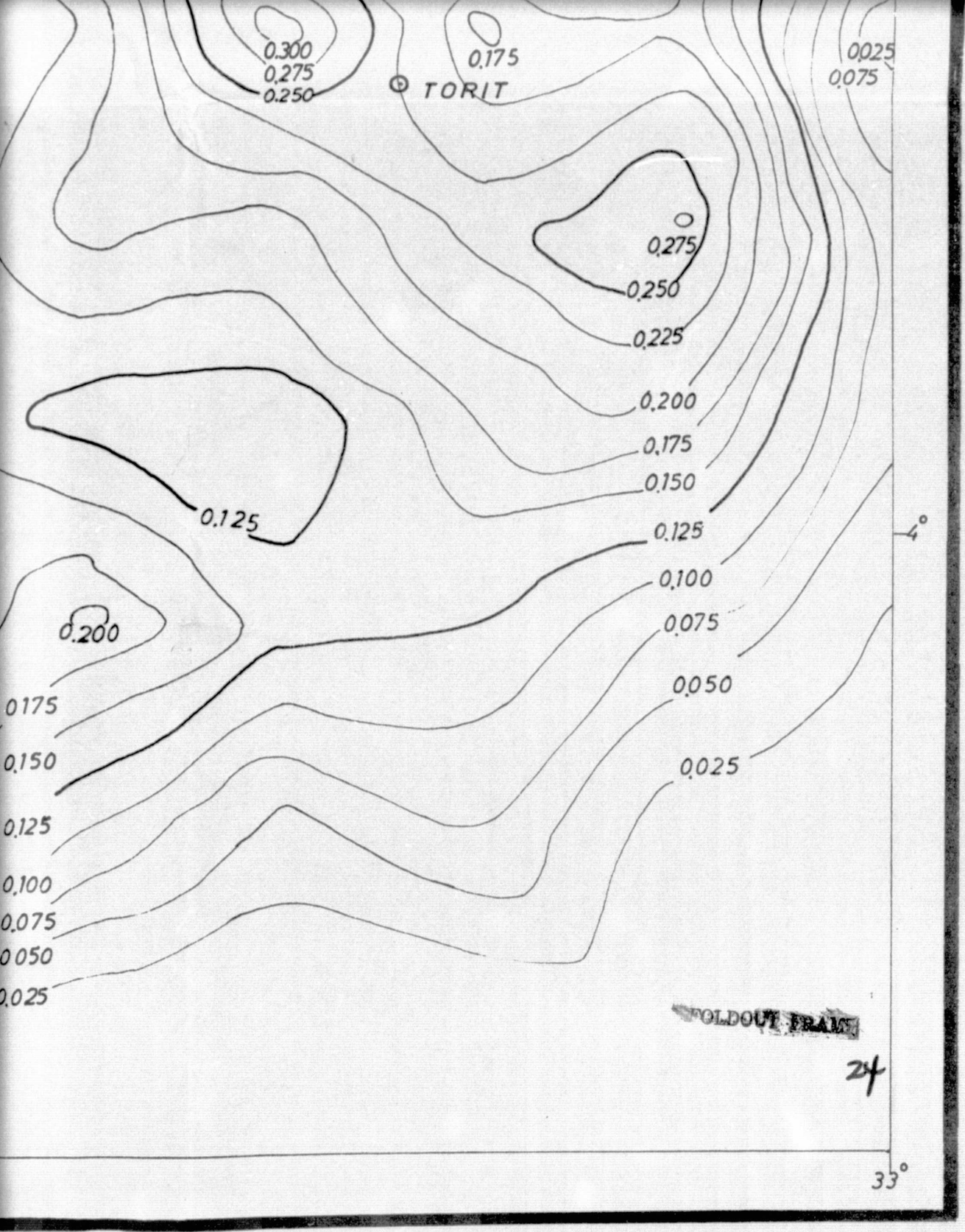
FIG. 4ª. LINEAMENT DENSIT



MENT DENSITY MAP OF THE JONGLEI CANAL



GLEI CANAL PROJECT AREA, SOUTHERN S OU



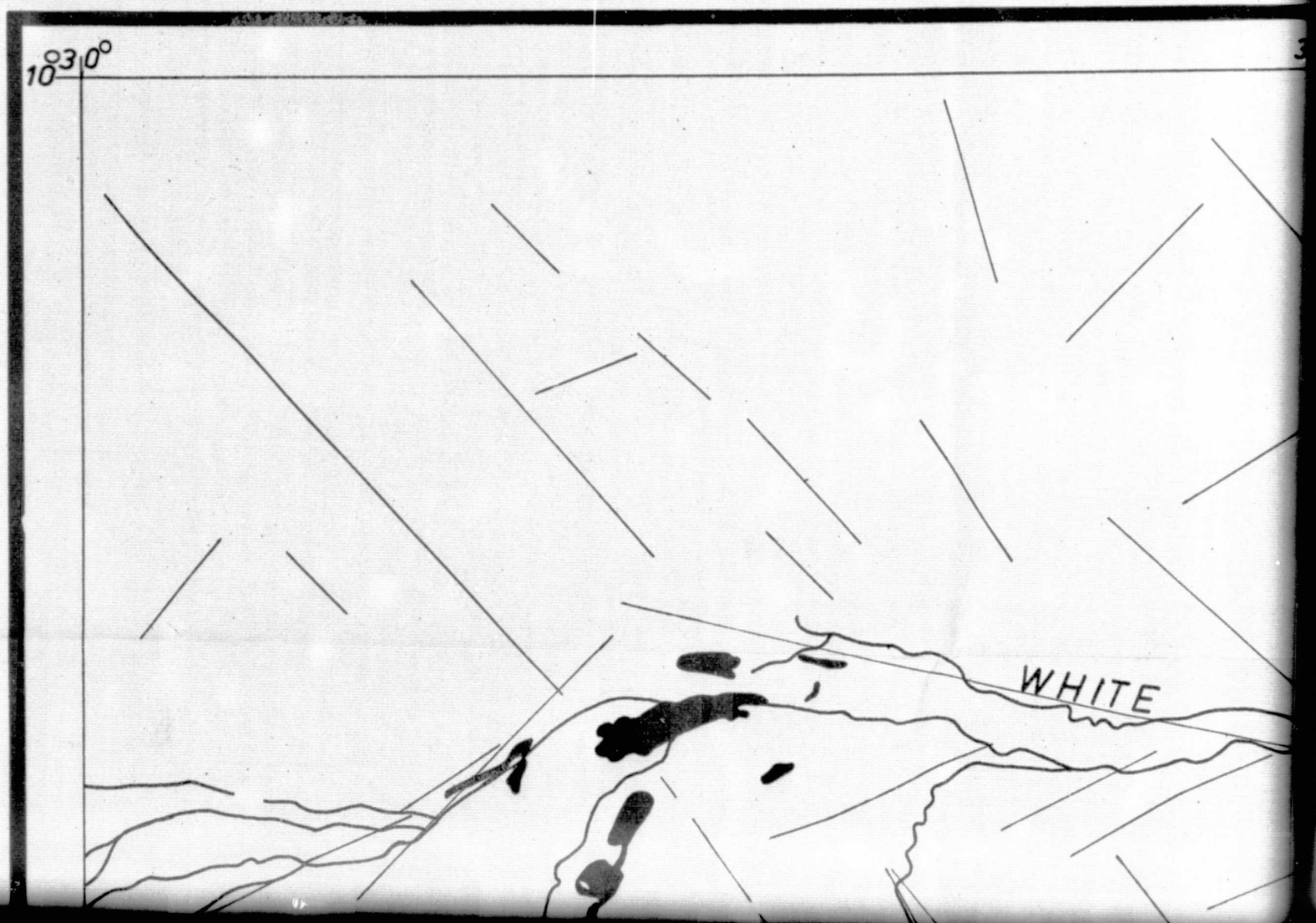
OUTHERN SUDAN .

FOLDOUT FRAME

FOLDOUT

REMOTE SENSING CENTER, CAIRO

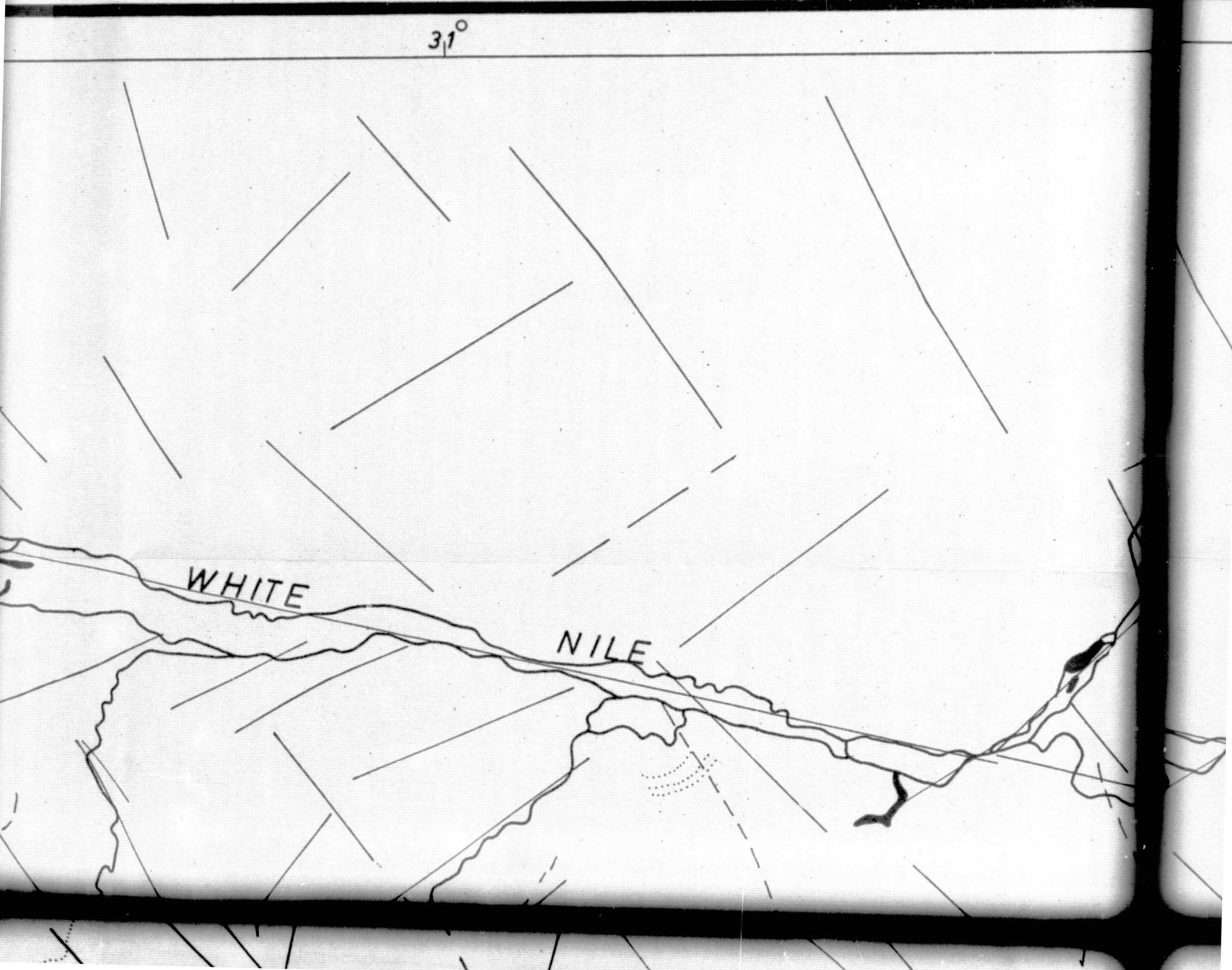
ACADEMY OF SCIENTIFIC RESEARCH AND TECHNOLOGY



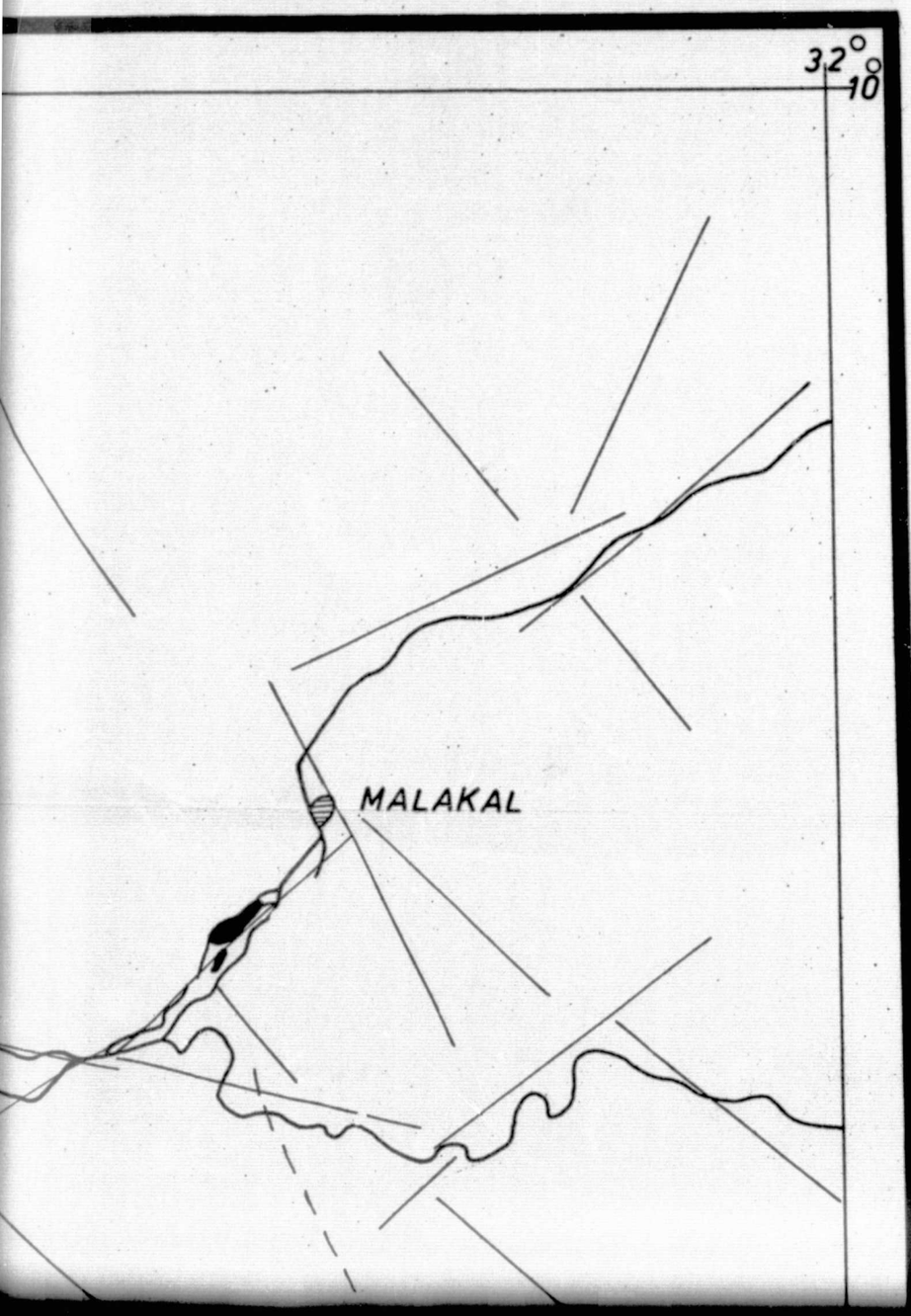
FOLDOUT FRAME 2

CENTER, CAIRO

EARCH AND TECHNOLOGY



FOLDOUT FRAME 3



MINISTRY OF IRRIGATION,
ARAB REPUBLIC OF EGYPT

THE PERMAN
COMMISSIO

FOLDOUT FRAME 7

FOLDOUT FRAME

4

RY OF IRRIGATION,
REPUBLIC OF EGYPT

MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS

CITIES AND TOWNS

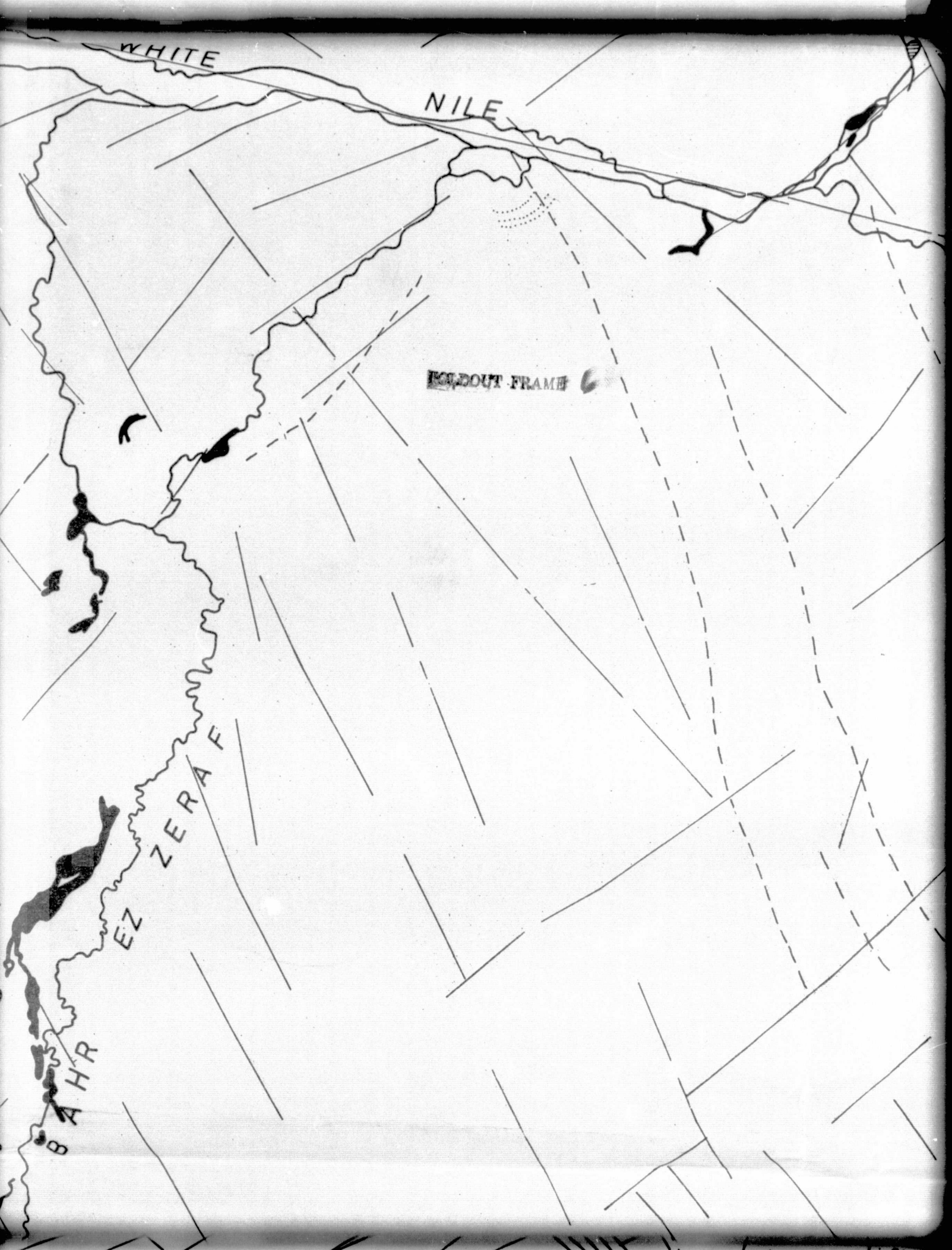
WHITE

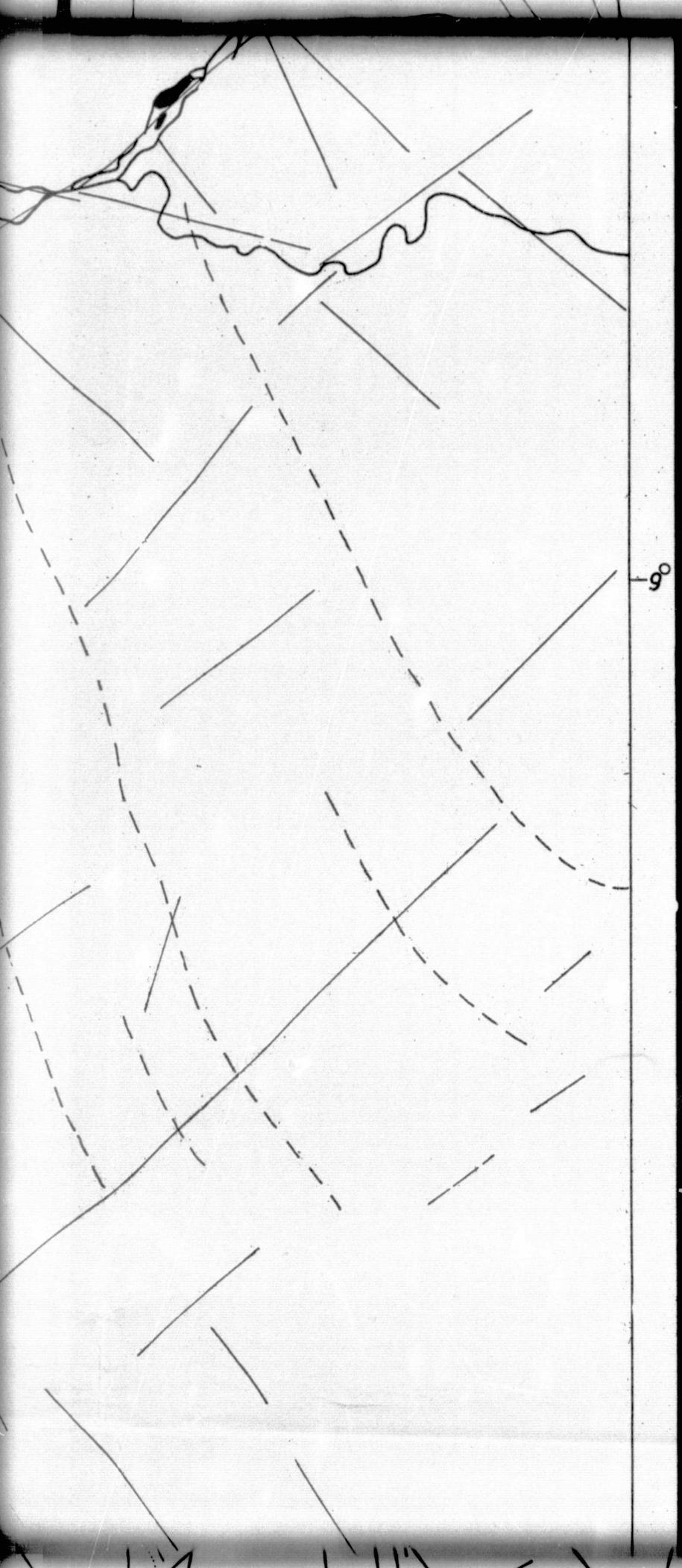
BAHR EL ZERAF

BAHR EL JEBEL

FOLDOUT FRAME

96


WHITE
NILE
FOLDOUT FRAME 6
BAHR EZ ZERAF

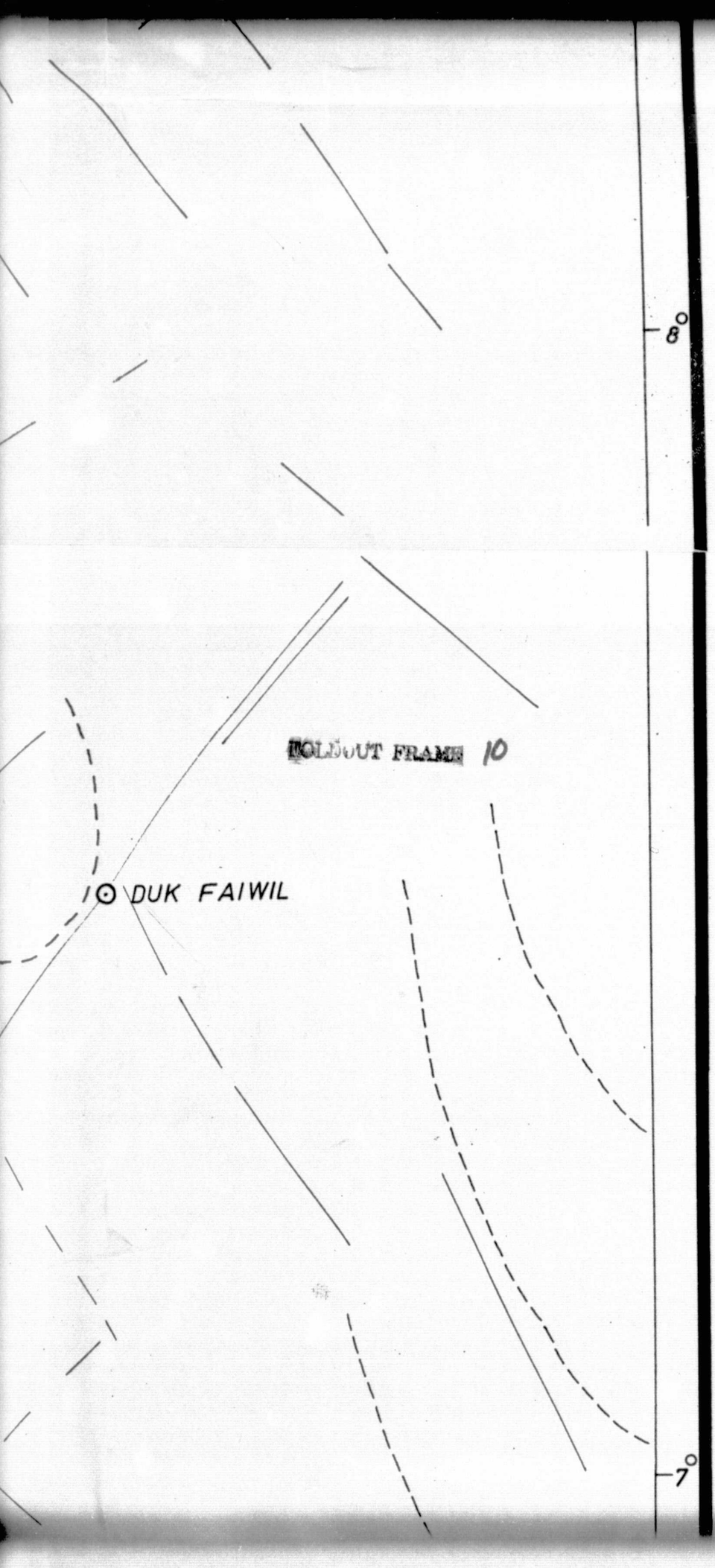


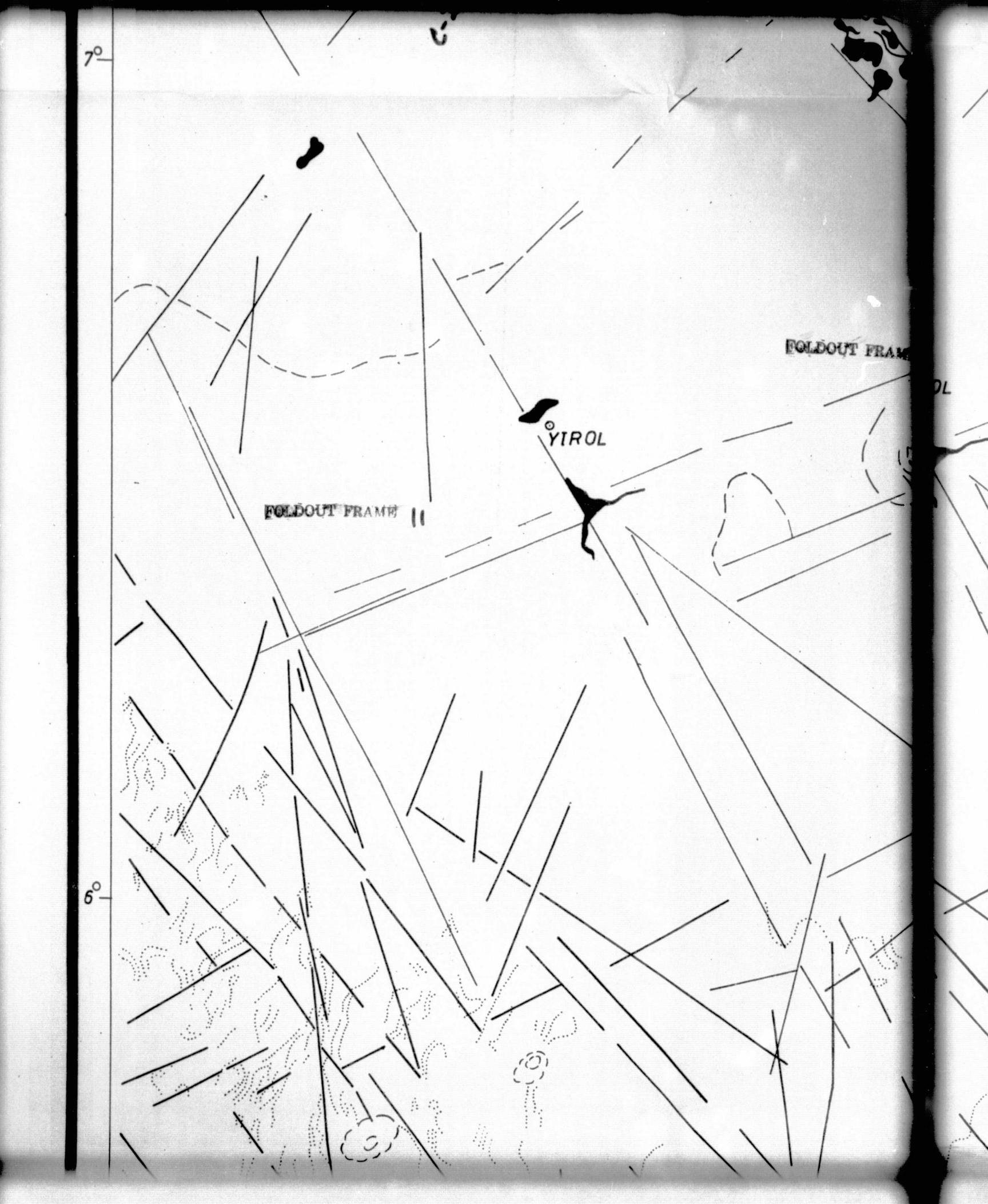
FOLDOUT FRAME 7

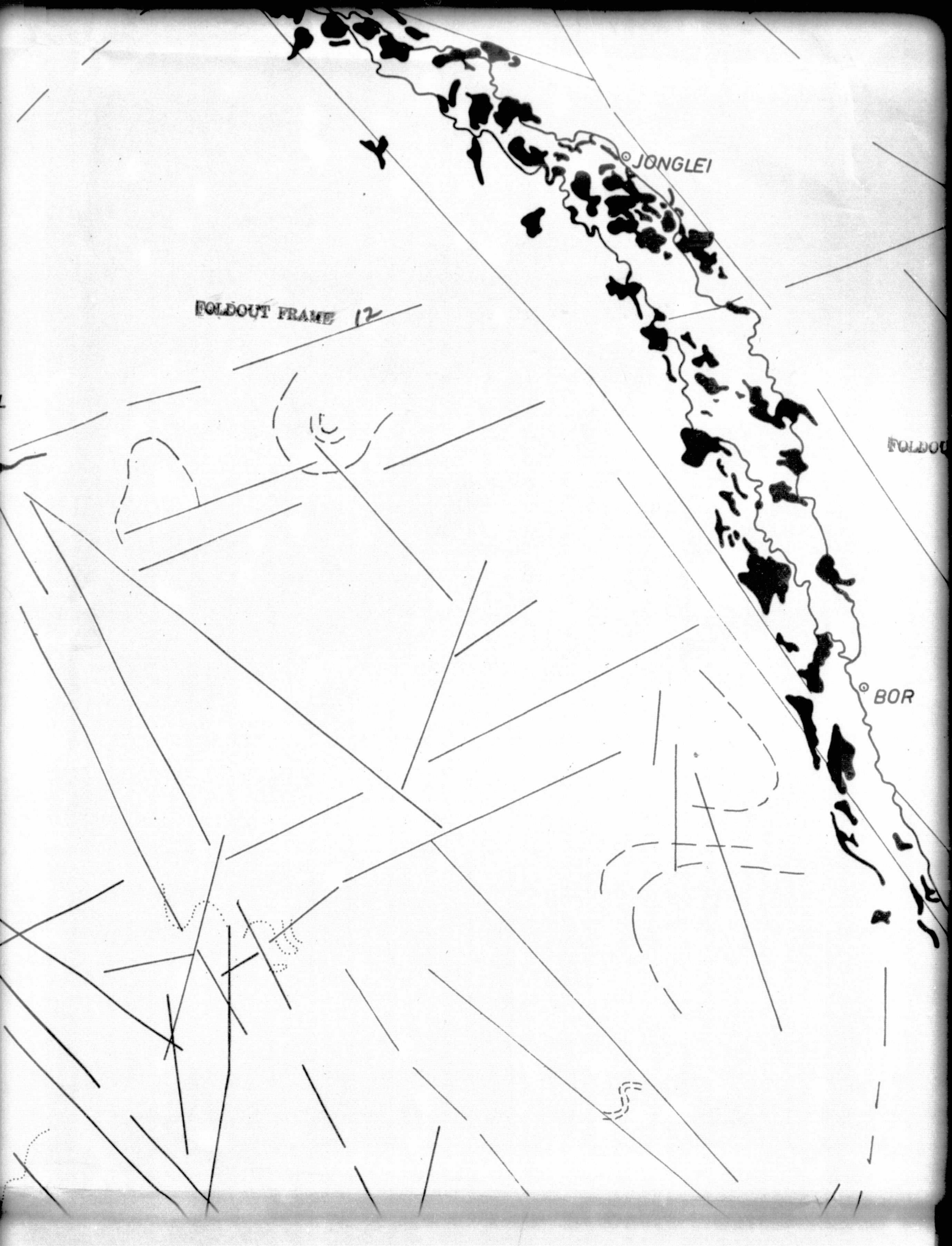
FOLDOUT FRAME 8

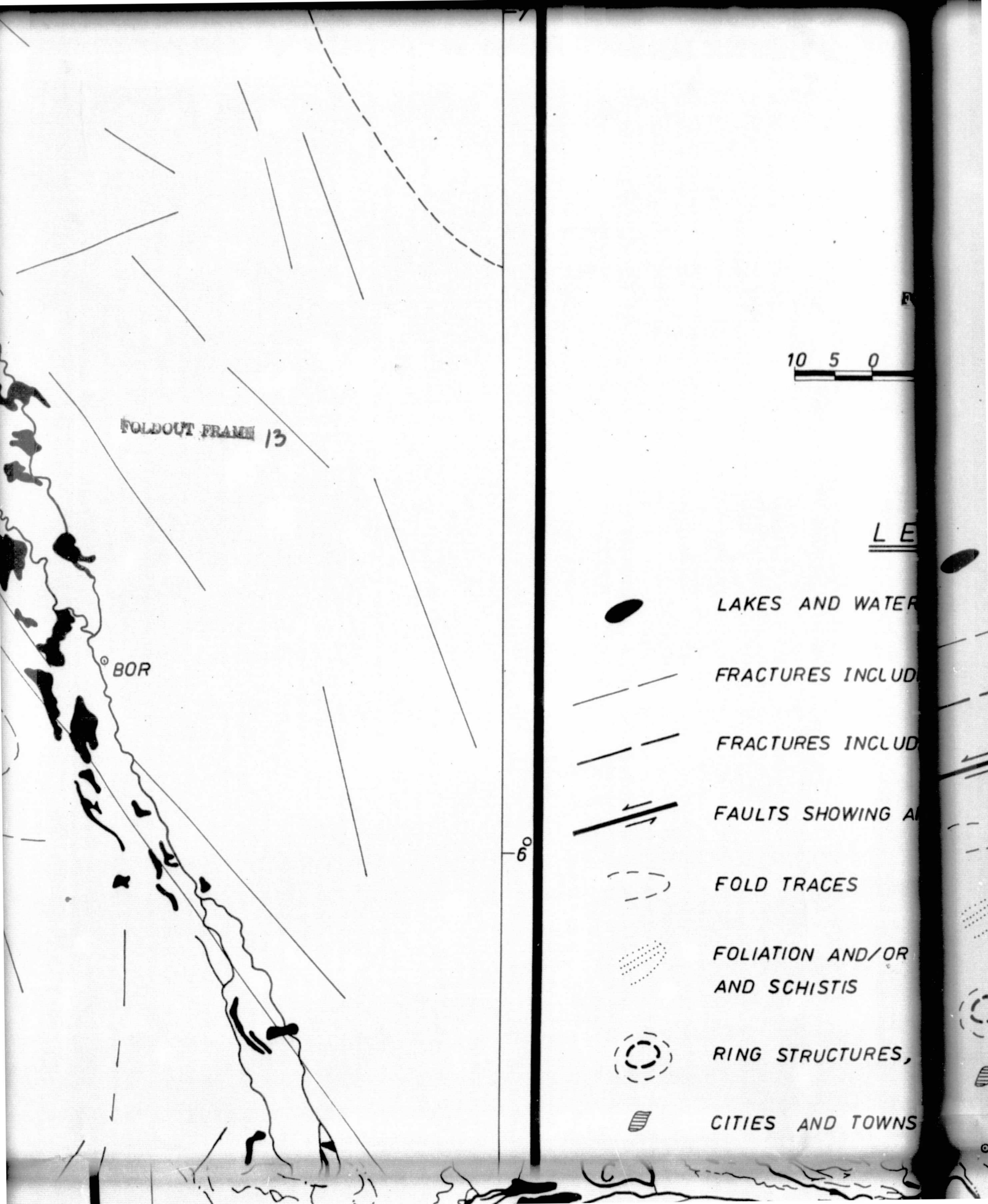
C-2


DUK F
FOLDOUT FRAME 9
KONGOR


8°
FOLDOUT FRAME 10
DUK FAIWIL
7°


7°
6°
YIROL
FOLDOUT FRAME
FOLDOUT FRAME


JONGLEI
FOLDOUT FRAME 12
BOR


FOLDOUT FRAME 13
BOR
10 5 0
LE
LAKES AND WATER
FRACTURES INCLUD
FRACTURES INCLUD
FAULTS SHOWING A
FOLD TRACES
FOLIATION AND/OR
AND SCHISTIS
RING STRUCTURES,
CITIES AND TOWNS
6°

FOLDOUT FRAME 14

10 5 0 10 20 30 40 50 Km

LEGEND

LAKES AND WATER PONDS

FRACTURES INCLUDING FAULTS IN SADIMENT

FRACTURES INCLUDING FAULTS IN BASEMENT

FAULTS SHOWING APPARENT HORIZONTAL SEPARATION

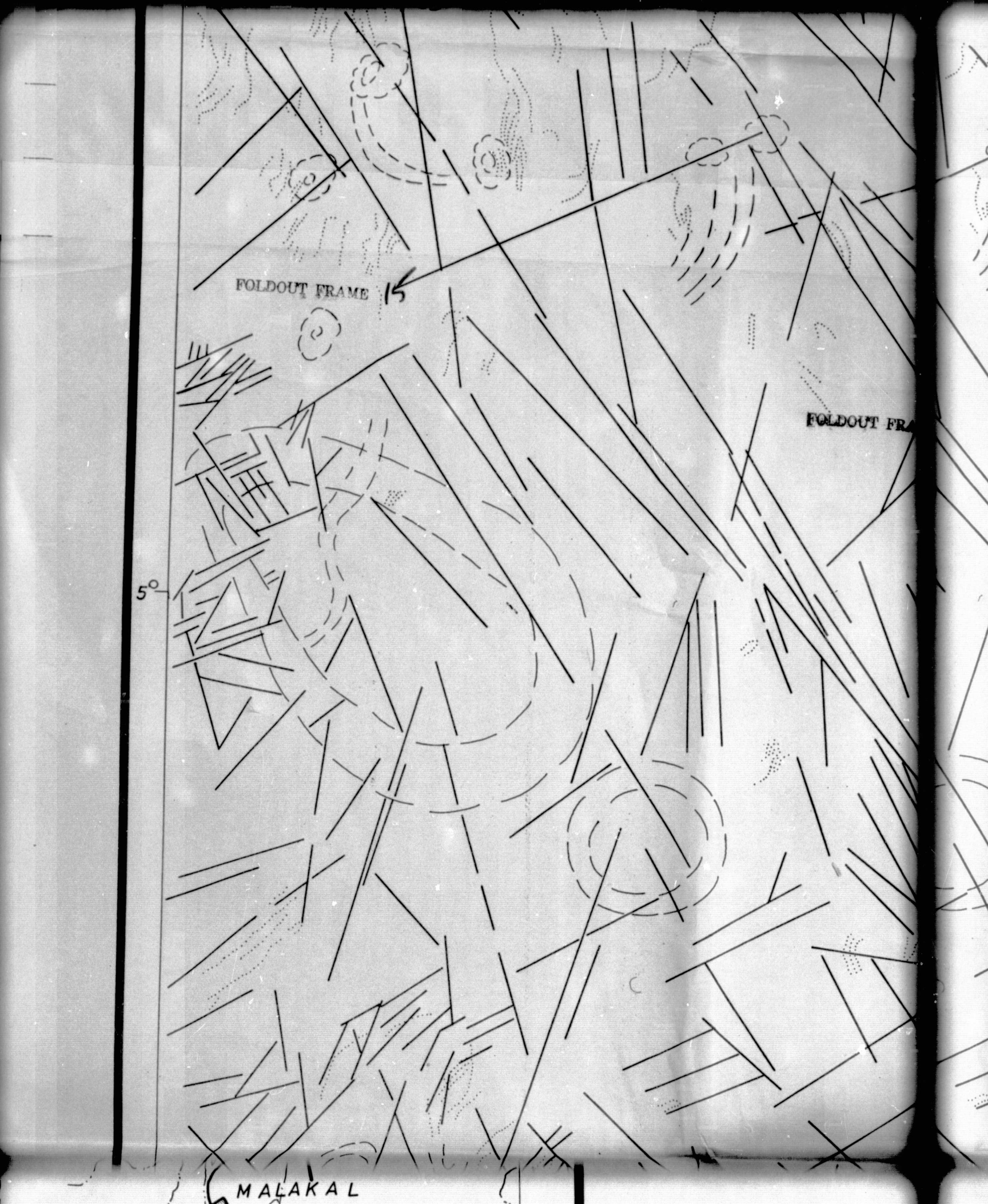
FOLD TRACES

FOLIATION AND/OR BEDDING TRACES IN GNEISSES AND SCHISTIS

RING STRUCTURES, DASHED WHERE INFERRED

CITIES AND TOWNS

SETTLEMENTS AND SMALL TOWNS


FOLDOUT FRAME 15
FOLDOUT FR
5°
MALAKAL

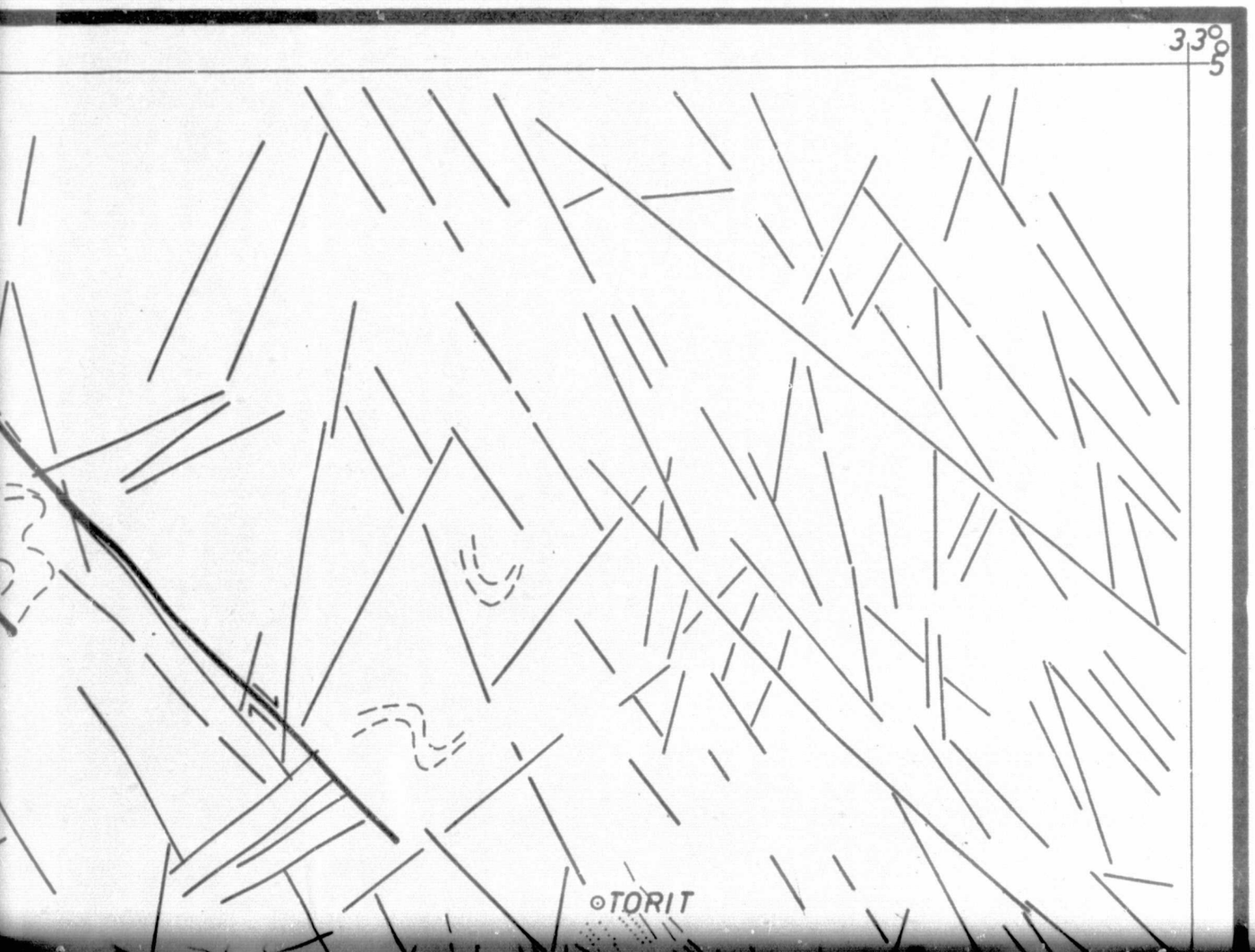

FOLDOUT FRAME 16
JUBA


CITIES AND
SETTLEMENTS AN
FOLDOUT FRAME 7
JUBA

CITIES AND TOWNS

SETTLEMENTS AND SMALL TOWNS

FOLDOUT FRAME 18



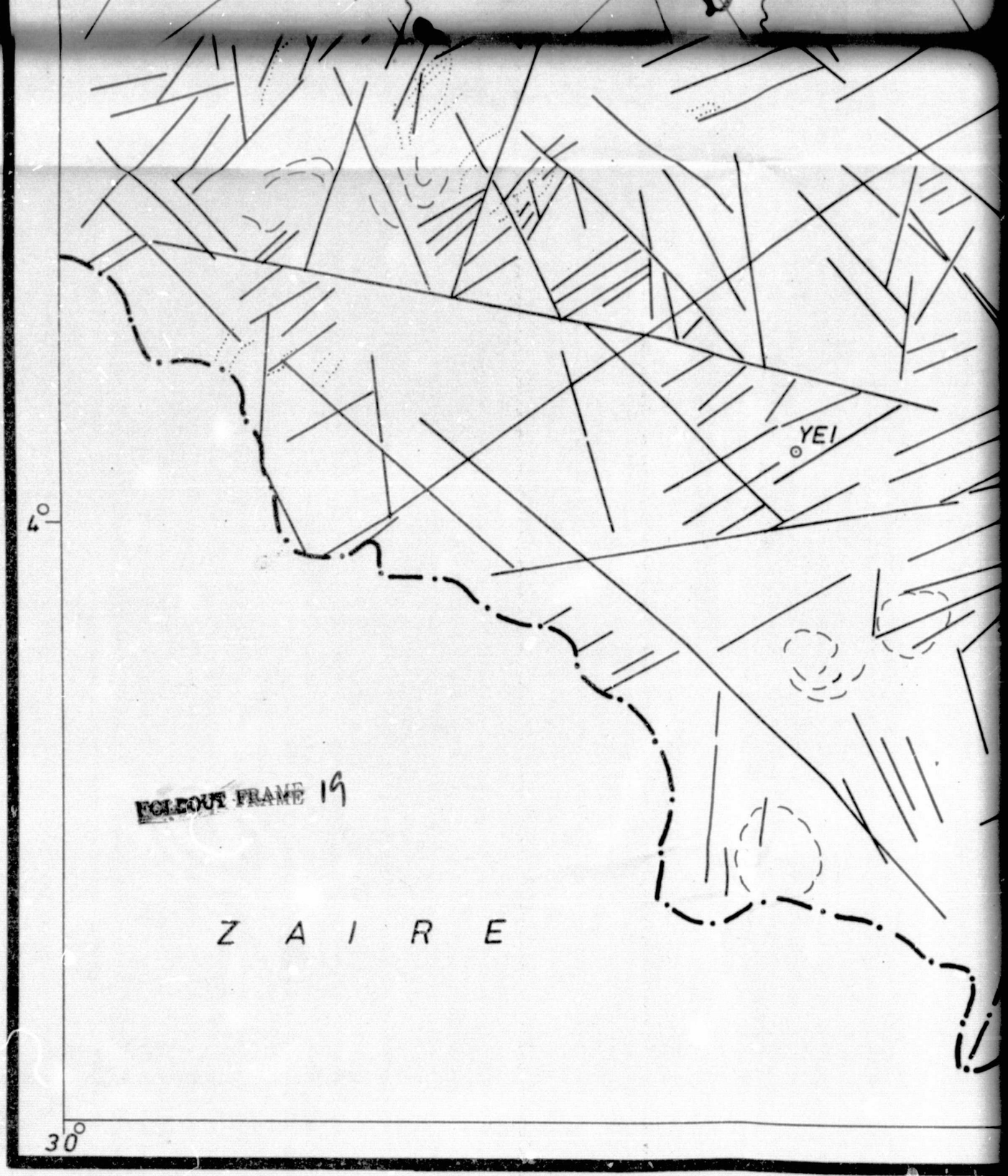
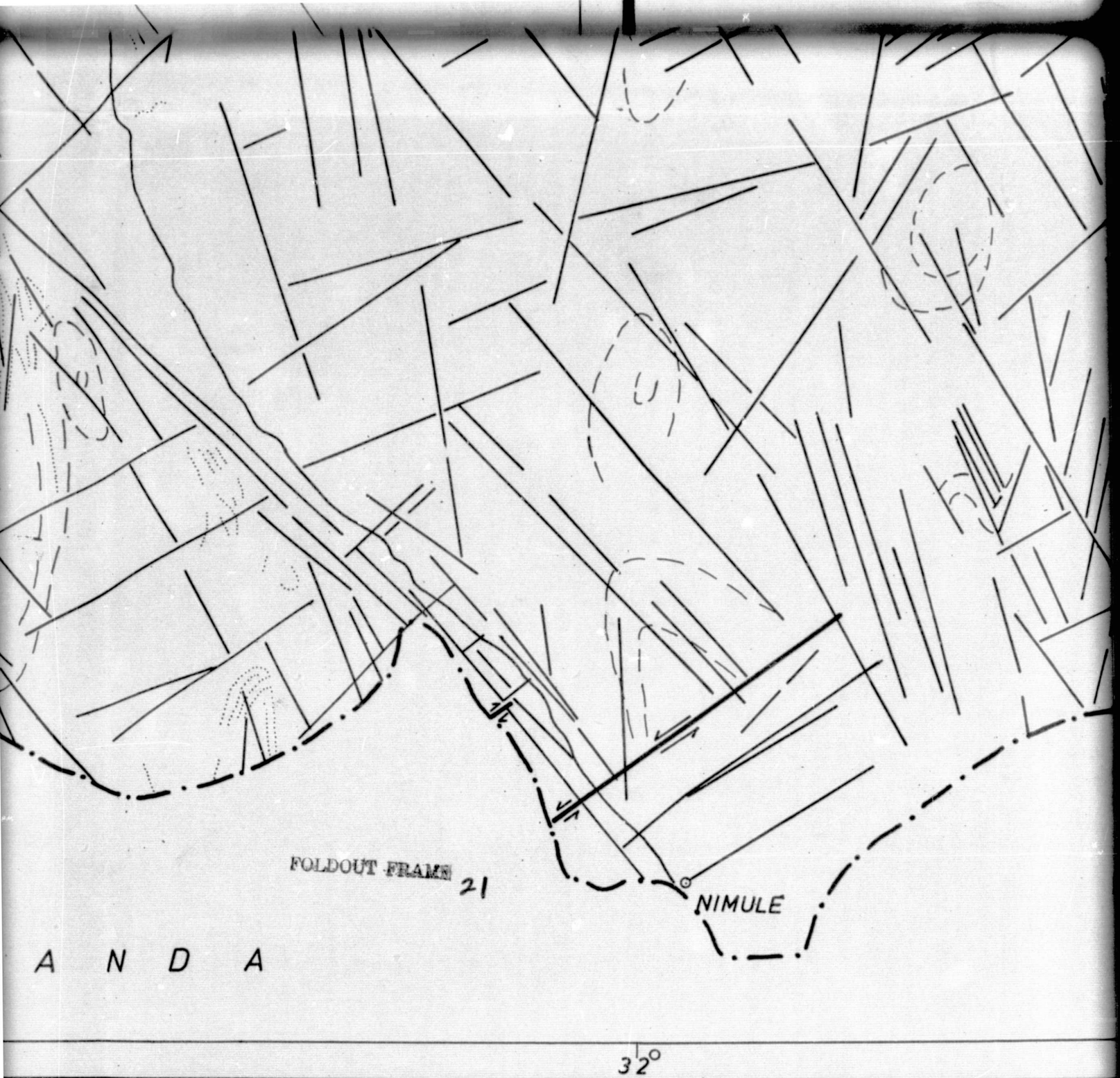


FIG. 3. STRUCTURAL LINE



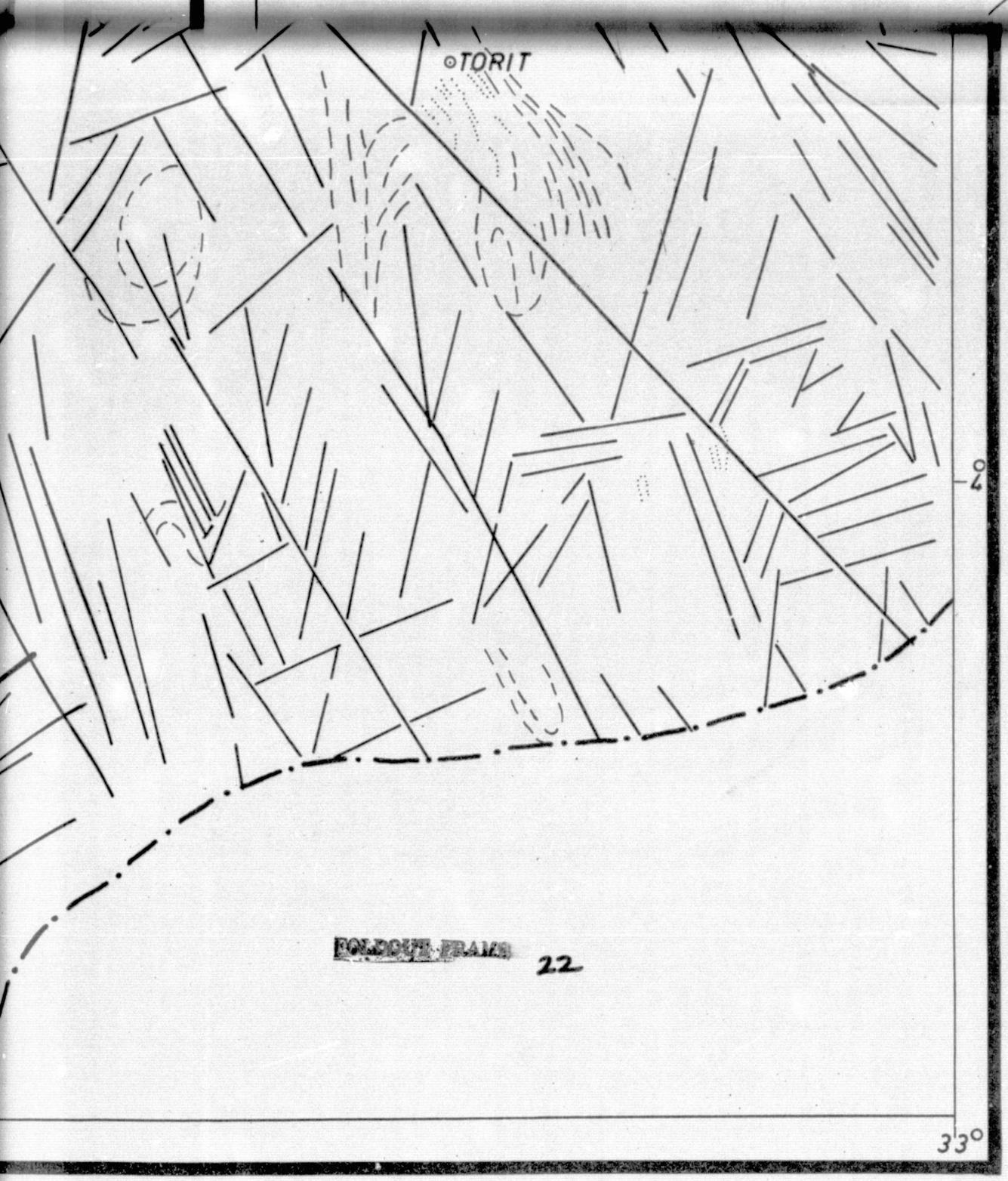
RAL LINEAMENT MAP OF THE JONG

(FROM LANDSAT SATELLITE I



HE JONGLEI CANAL PROJECT AREA, S CT

ELLITE IMAGES, FEBRUARY 1973) 3



FOLDOUT FRAME 22

CT AREA, SOUTHERN SUDAN

3 1

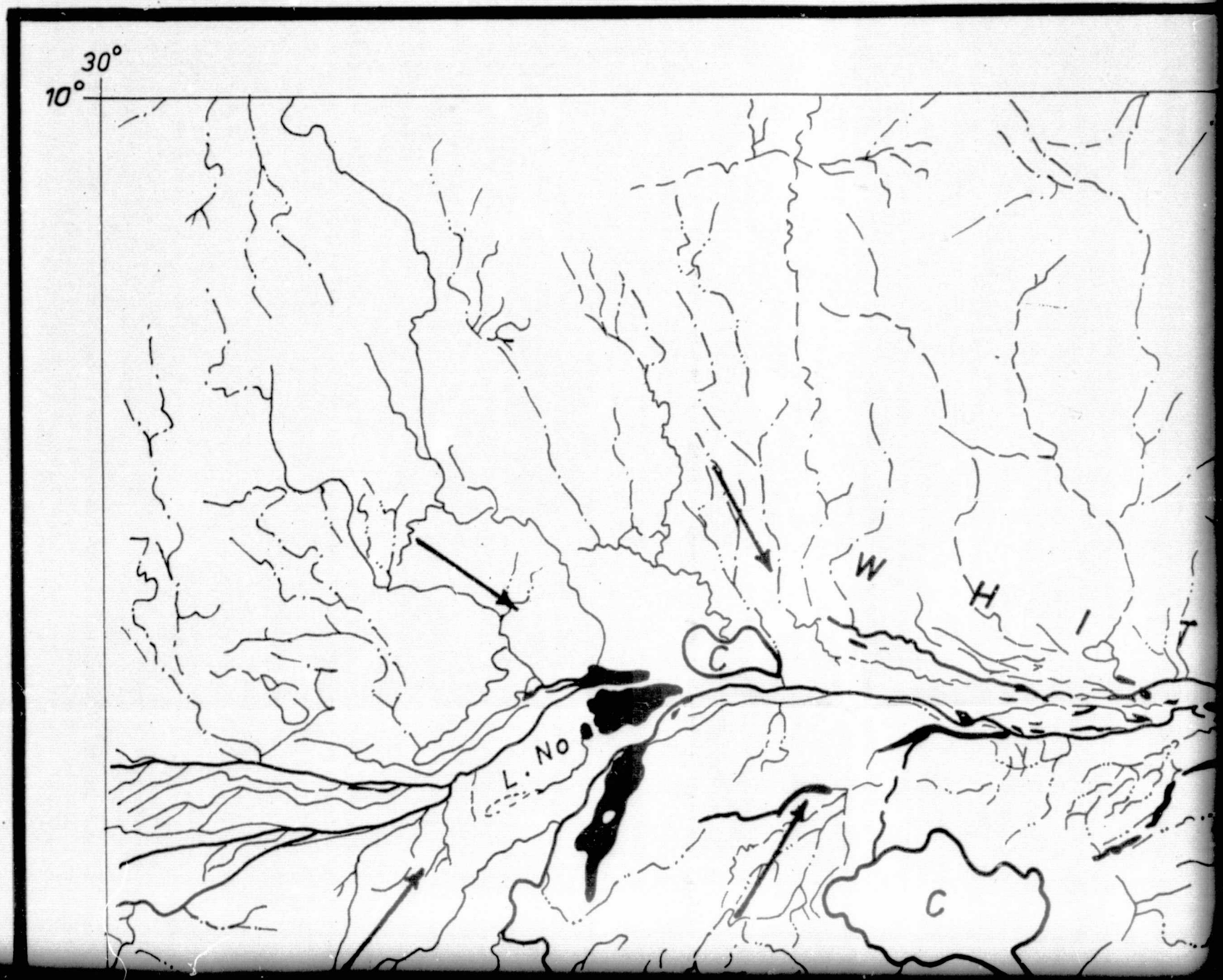
FOLDOUT FRAME 1

FOLDOUT FRAME 2

REMOTE SENSING CENTER

ACADEMY OF SCIENTIFIC RESEARCH AND TECHNOLOGY

CAIRO - EGYPT

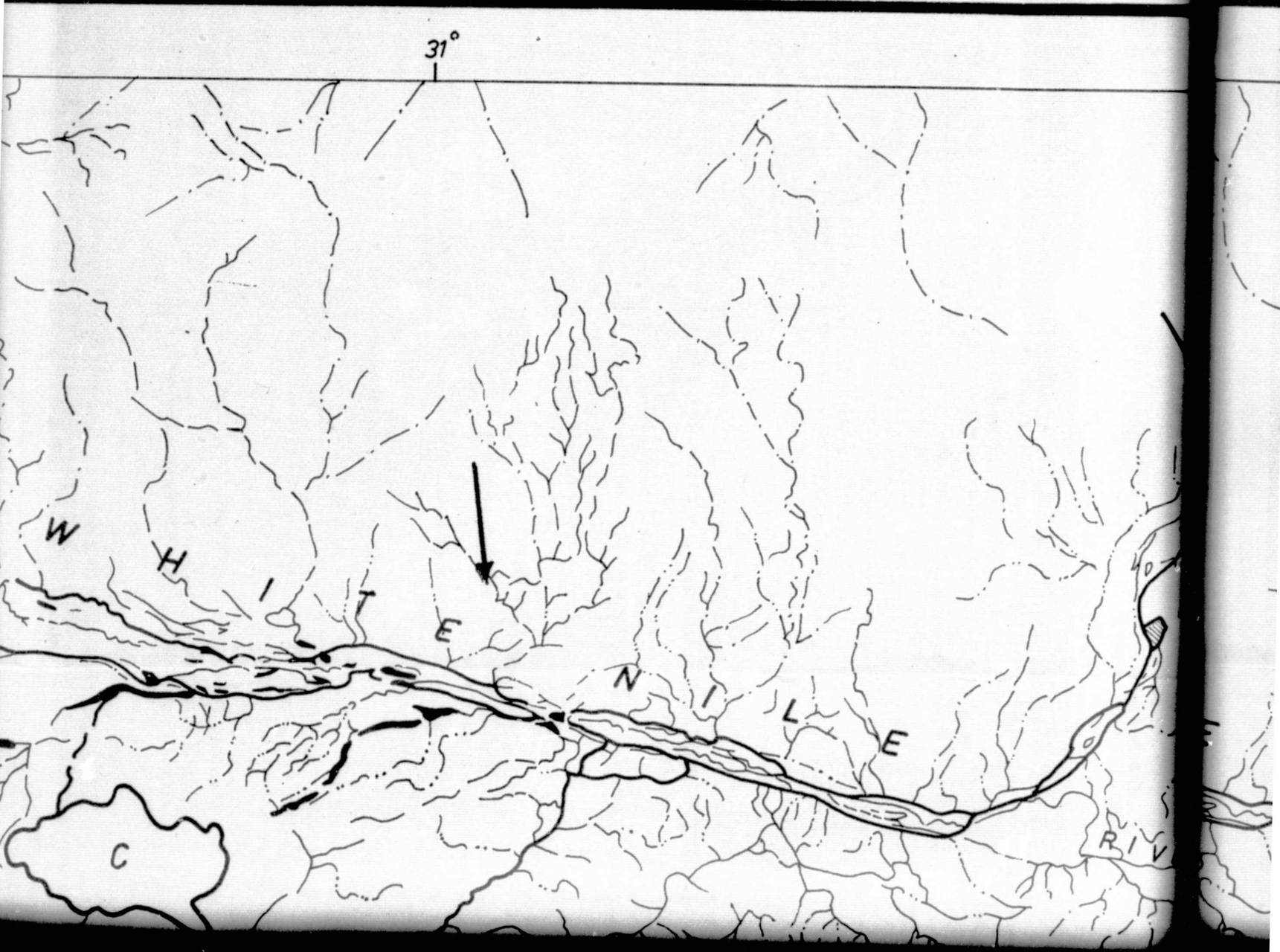


FOLDOUT FRAME 2

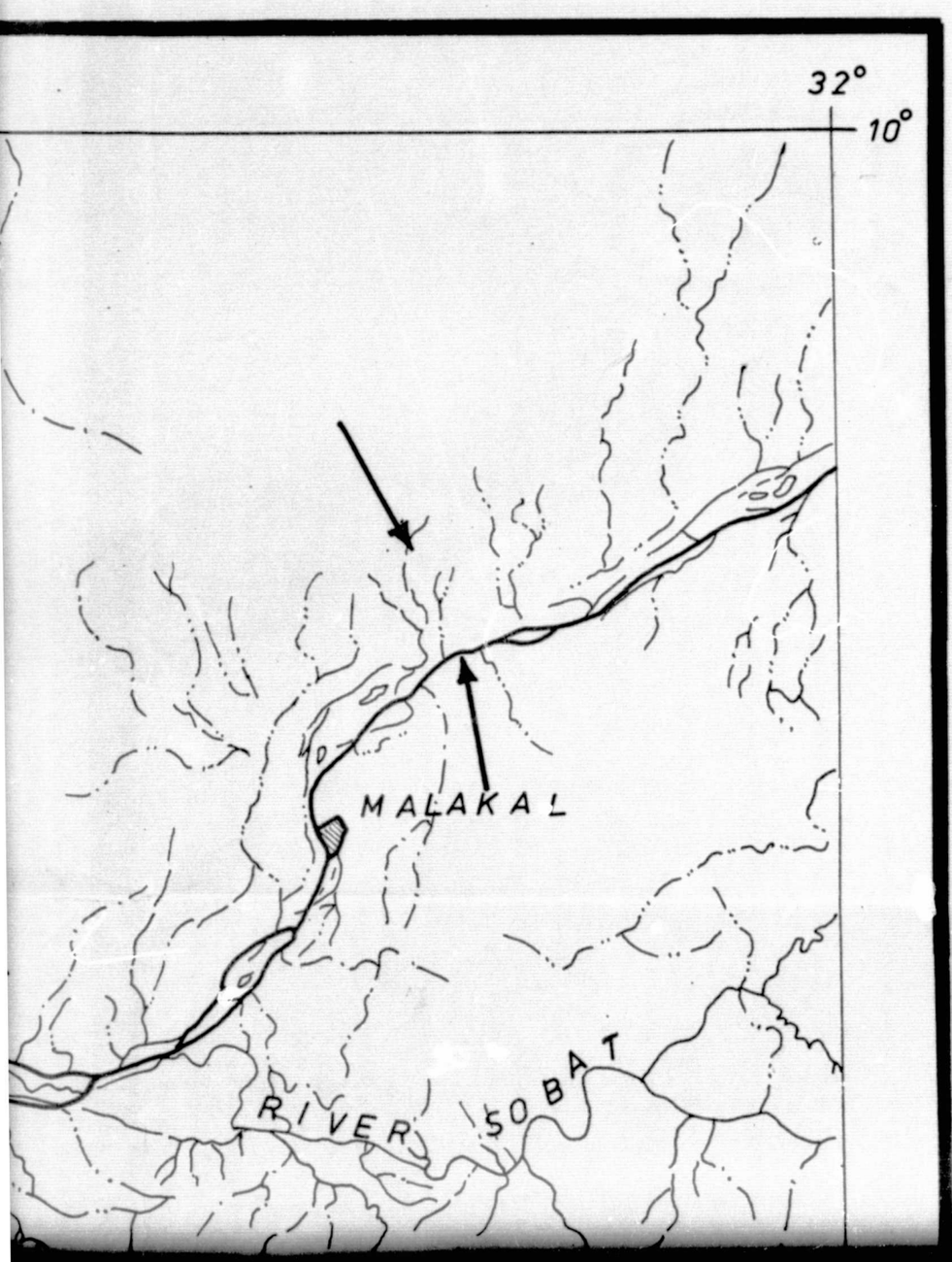
CENTER

RCH AND TECHNOLOGY

YPT



FOLDOUT FRAME 3



MINISTRY OF IRRIGATIO
ARAB REPUBLIC OF EGYPT

THE PER
COMMIS

[redacted] OUT FRAME 4

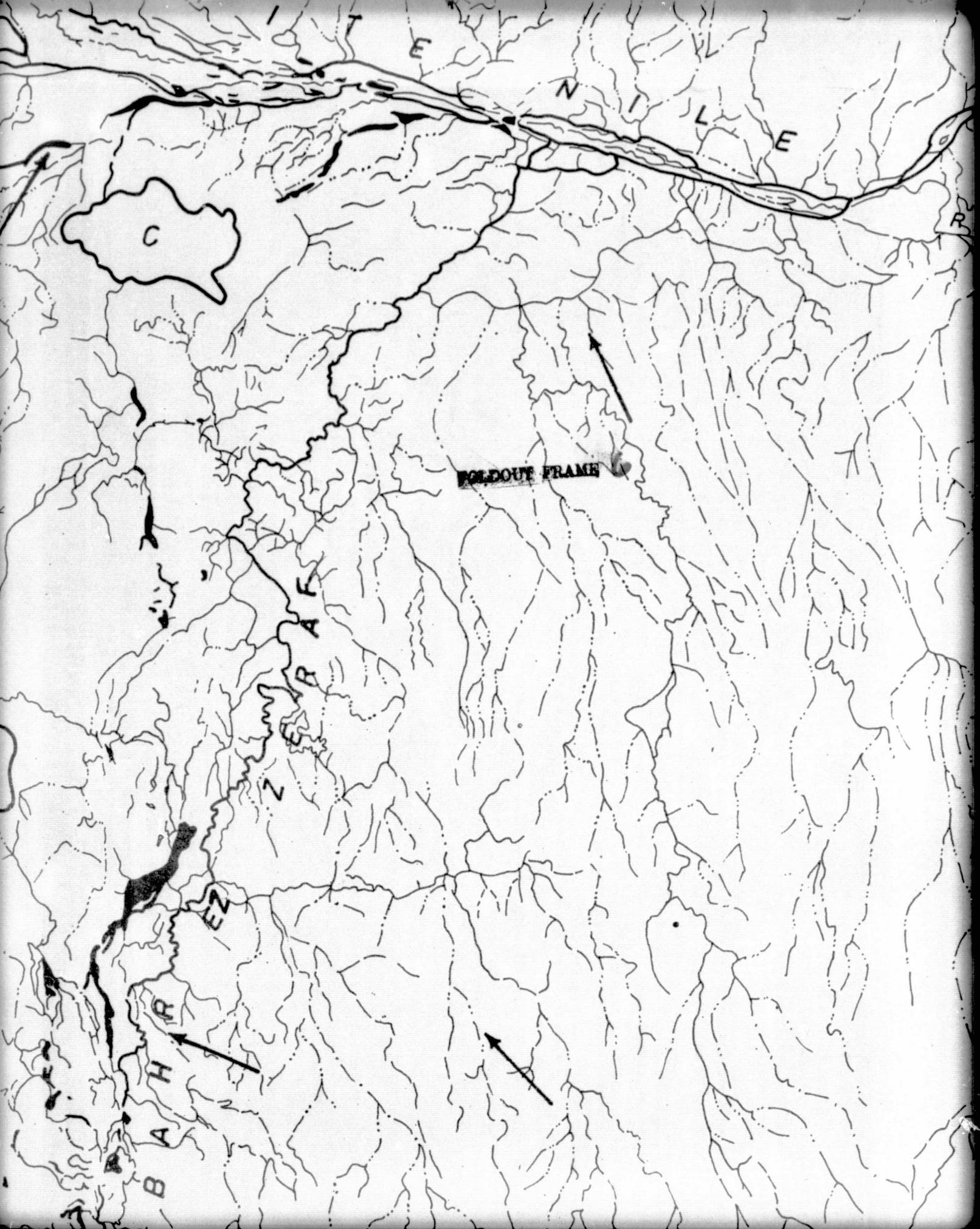
IISTRY OF IRRIGATION,
AB REPUBLIC OF EGYPT

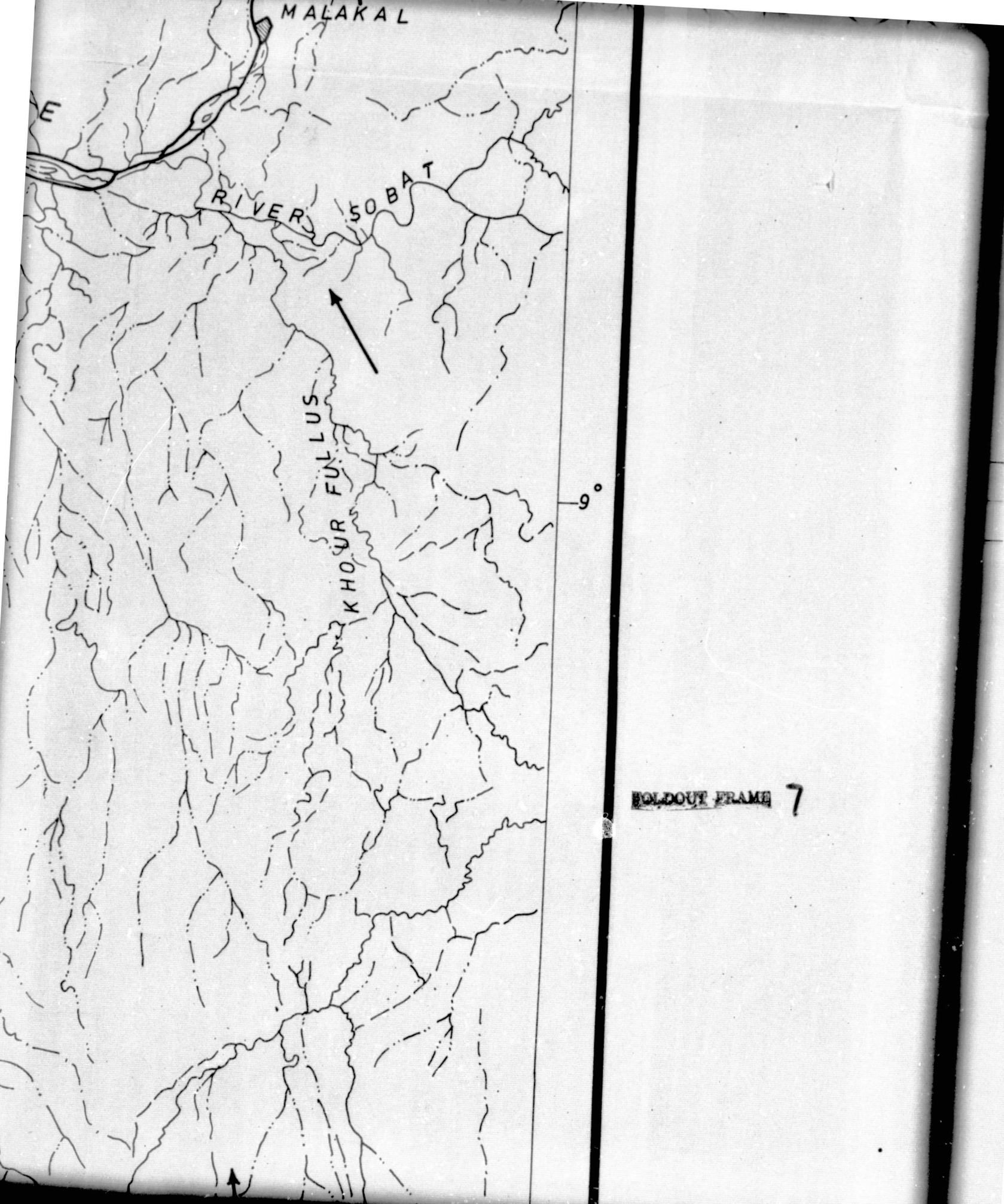
MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUPLIC

THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS

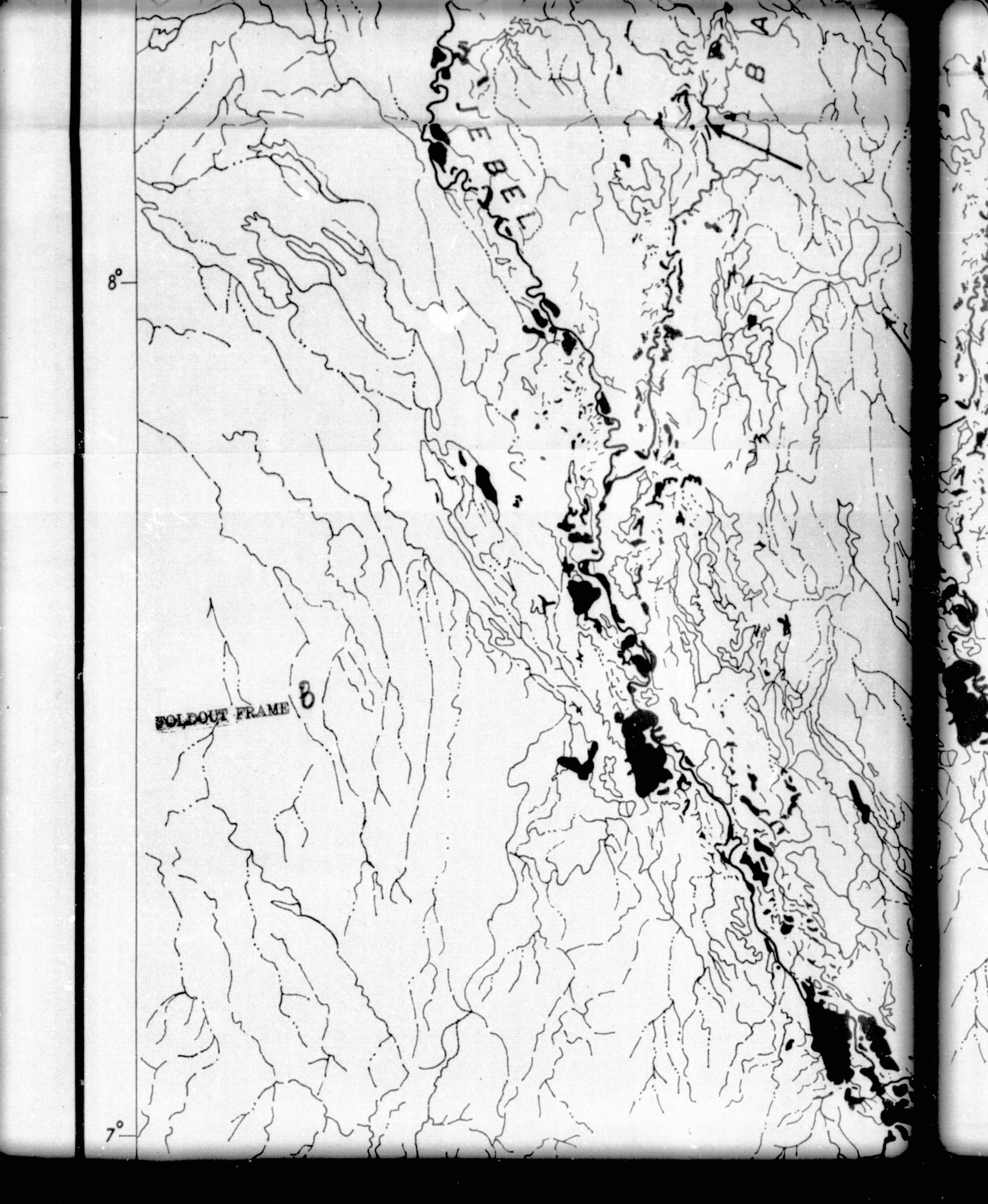
ORIGINAL PAGE IS
OF POOR QUALITY

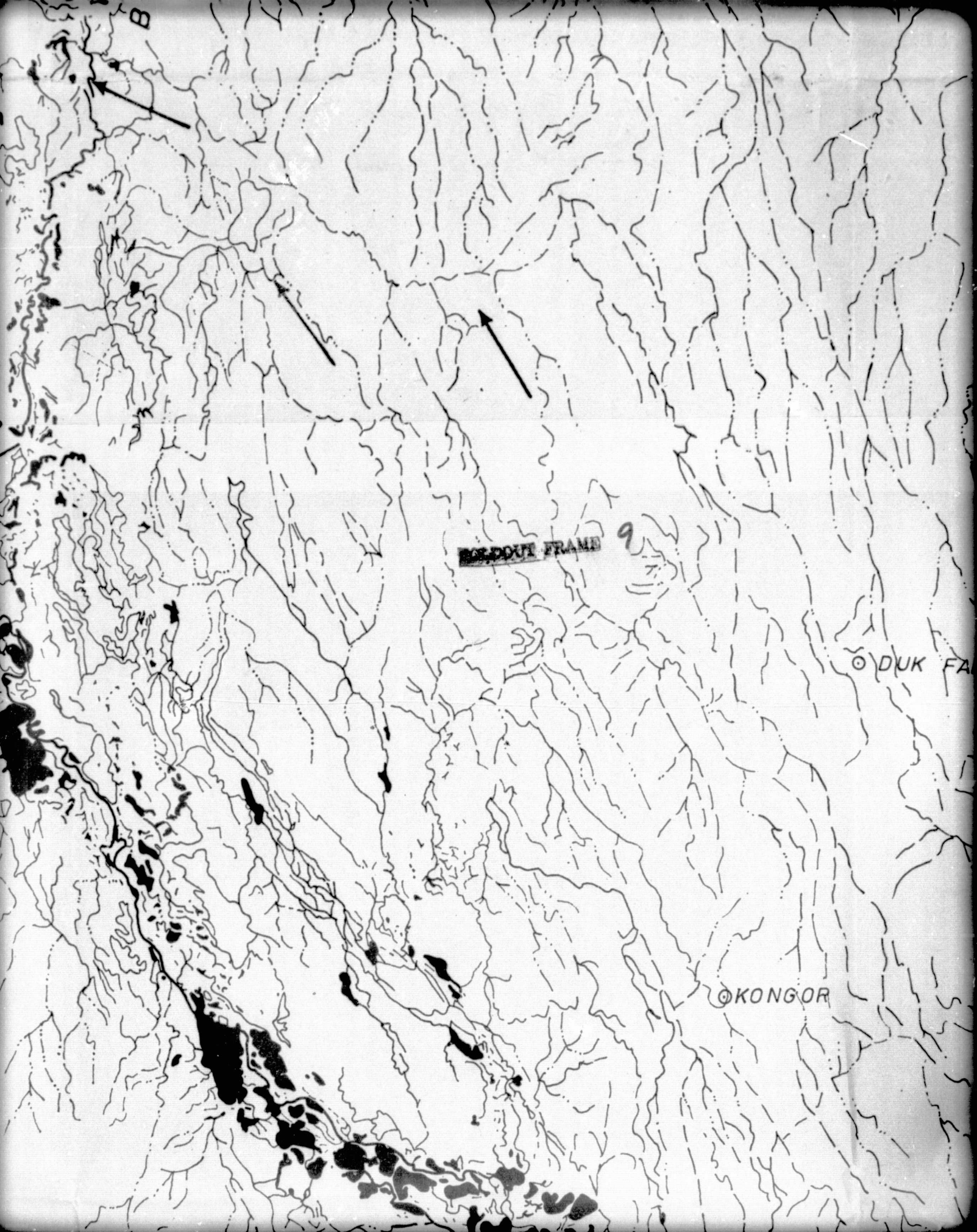
L. No
C
C
C
C
C
9°
BAHR
BAHR EZ
FOLDOUT FRAME 5

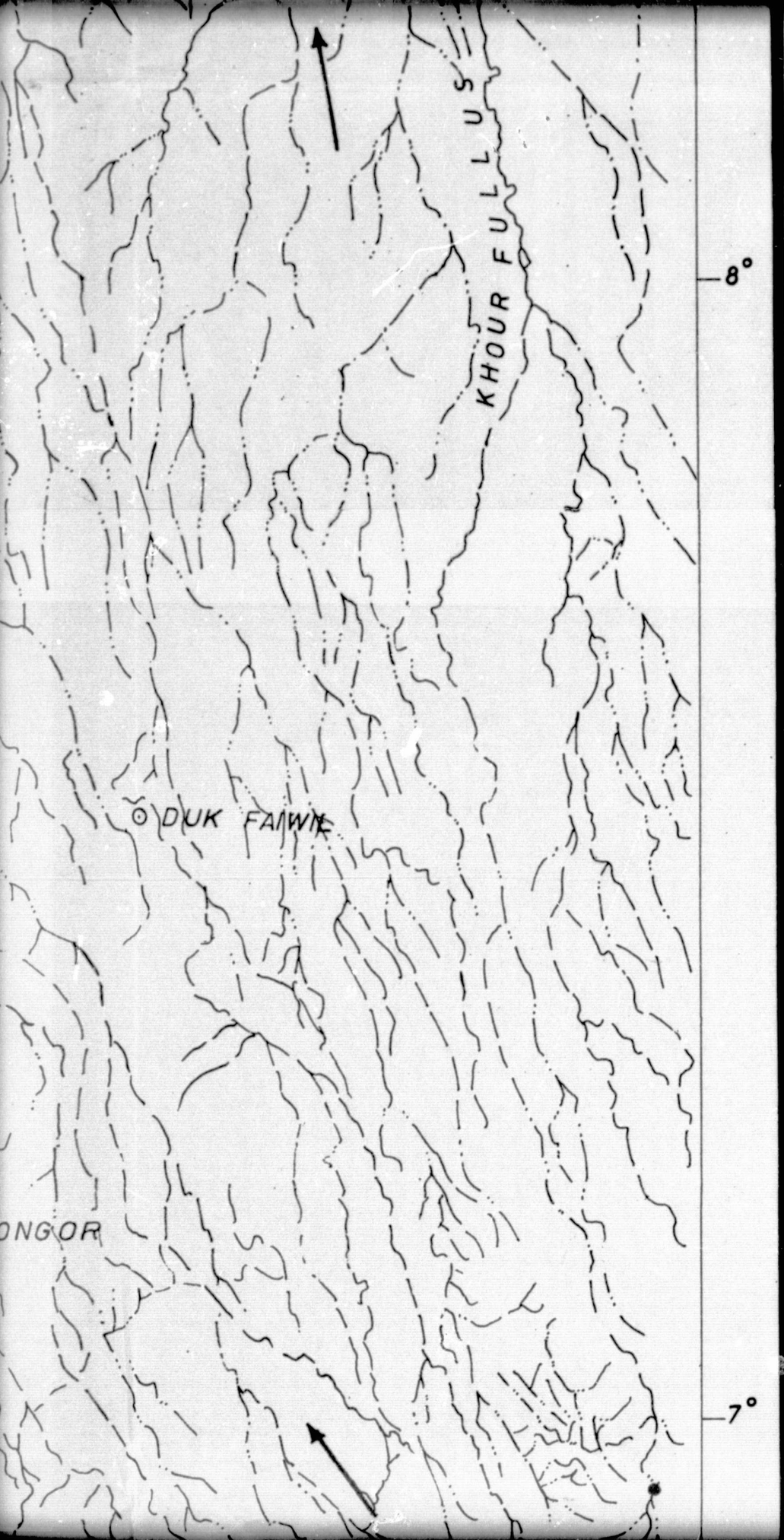

NILE
C
FOLDOUT FRAME
BAHR EZ ZERAF



FOLDOUT FRAME 7


JEBEL
B
8°
FOLDOUT FRAME
7°


B
DUK FA
KONGOR



FOLDOUT FRAME 10

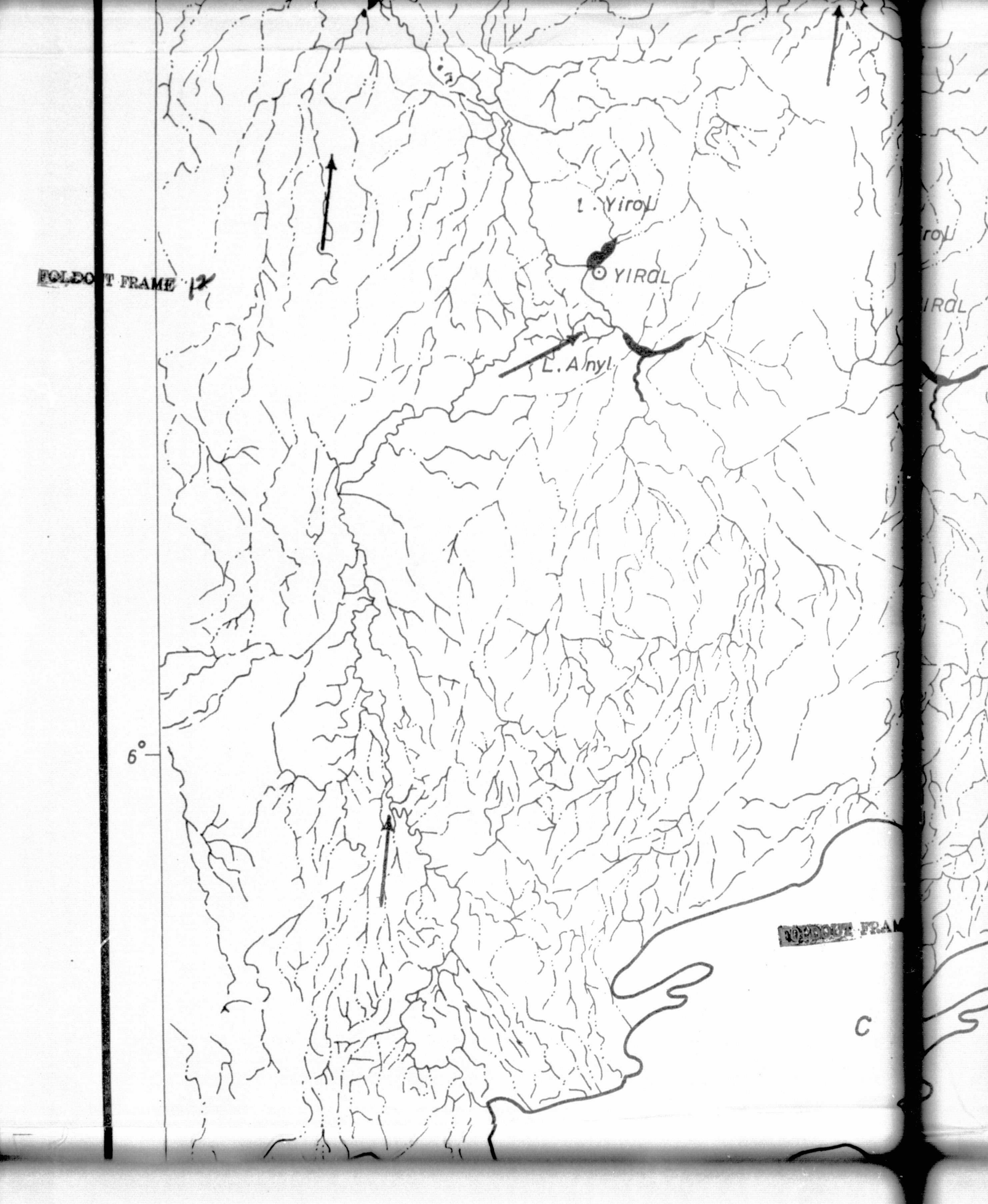
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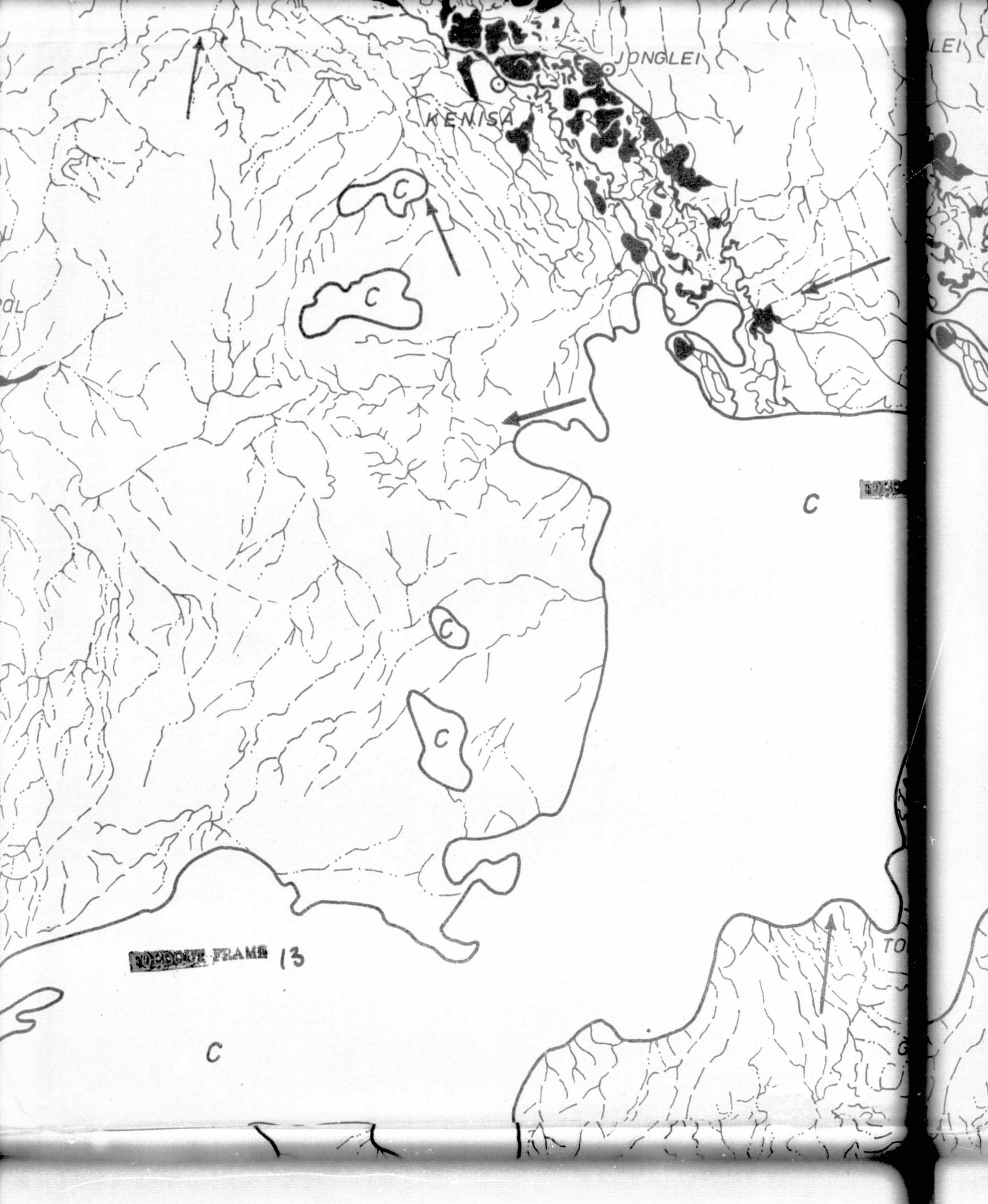
ORIGINAL PAGE IS
OF POOR QUALITY

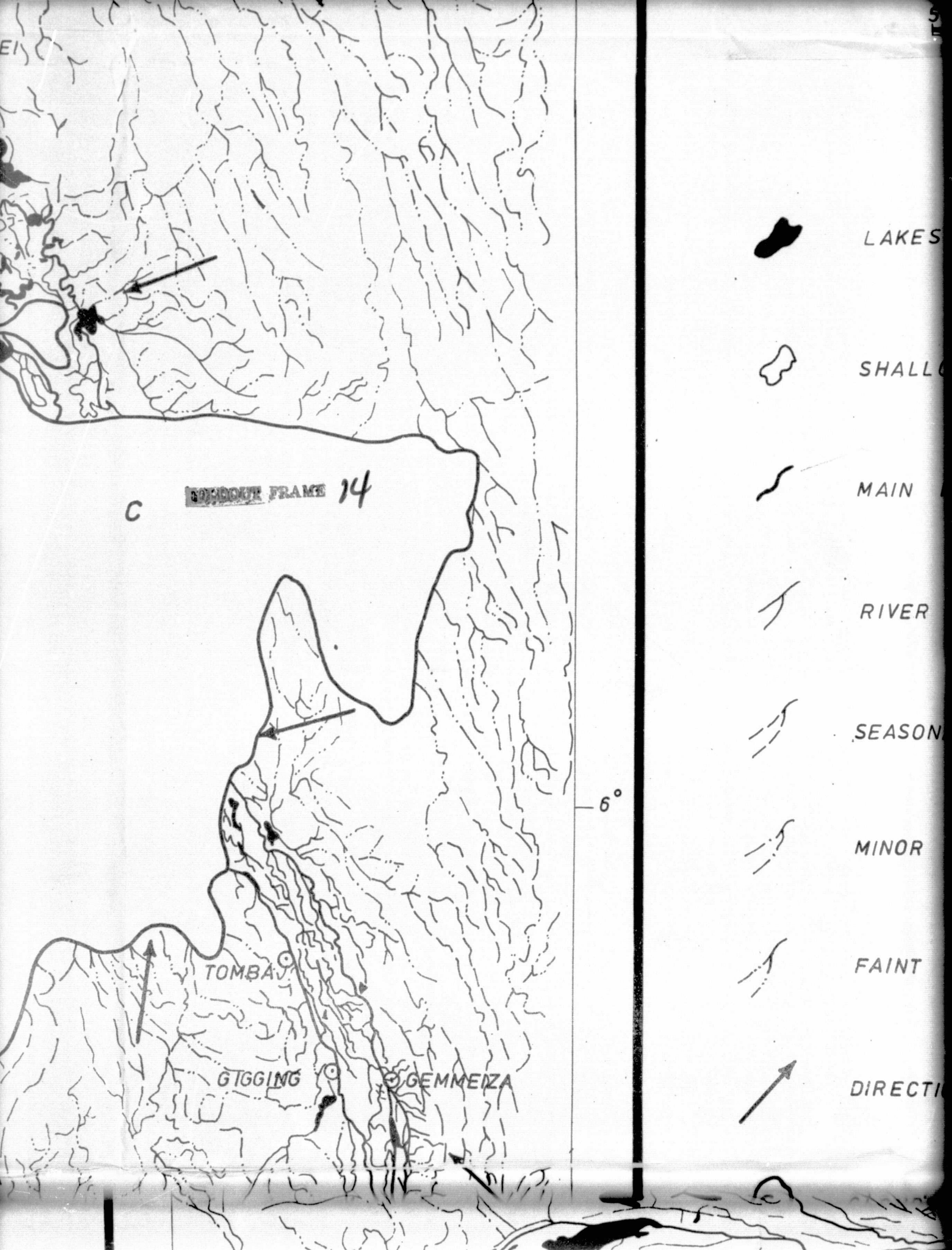
C-3

5 0 5 10 15 20 25 30 35 Km

LEGEND


L. Yiroll
YIRDL
L. Anyl
6°
C


JONGLEI
KENISA
C
C
C
C
C
C
FRAME 13


LAKES
SHALL
MAIN
RIVER
SEASON
MINOR
FAINT
DIRECTI
6°
TOMBA
GIGGING
GEMMEIZA
C
FRAME 14

5 0 5 10 15 20 25 30 35 Km

LEGEND



LAKES AND WATER PONDS



SHALLOW WATER BODIES

FOLDOUT FRAME 15



MAIN RIVER CHANNELS



RIVER CHANNELS AND PERENNIAL STREAMS



SEASONAL STREAMS



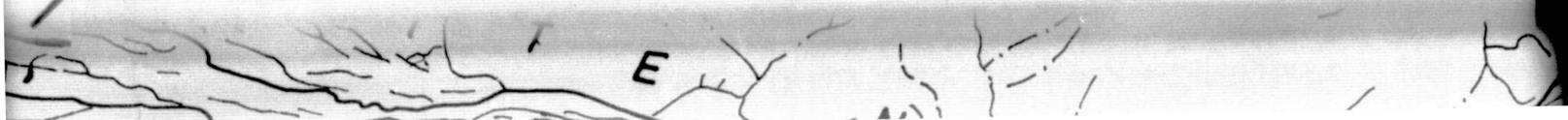
MINOR DRAINAGE LINES

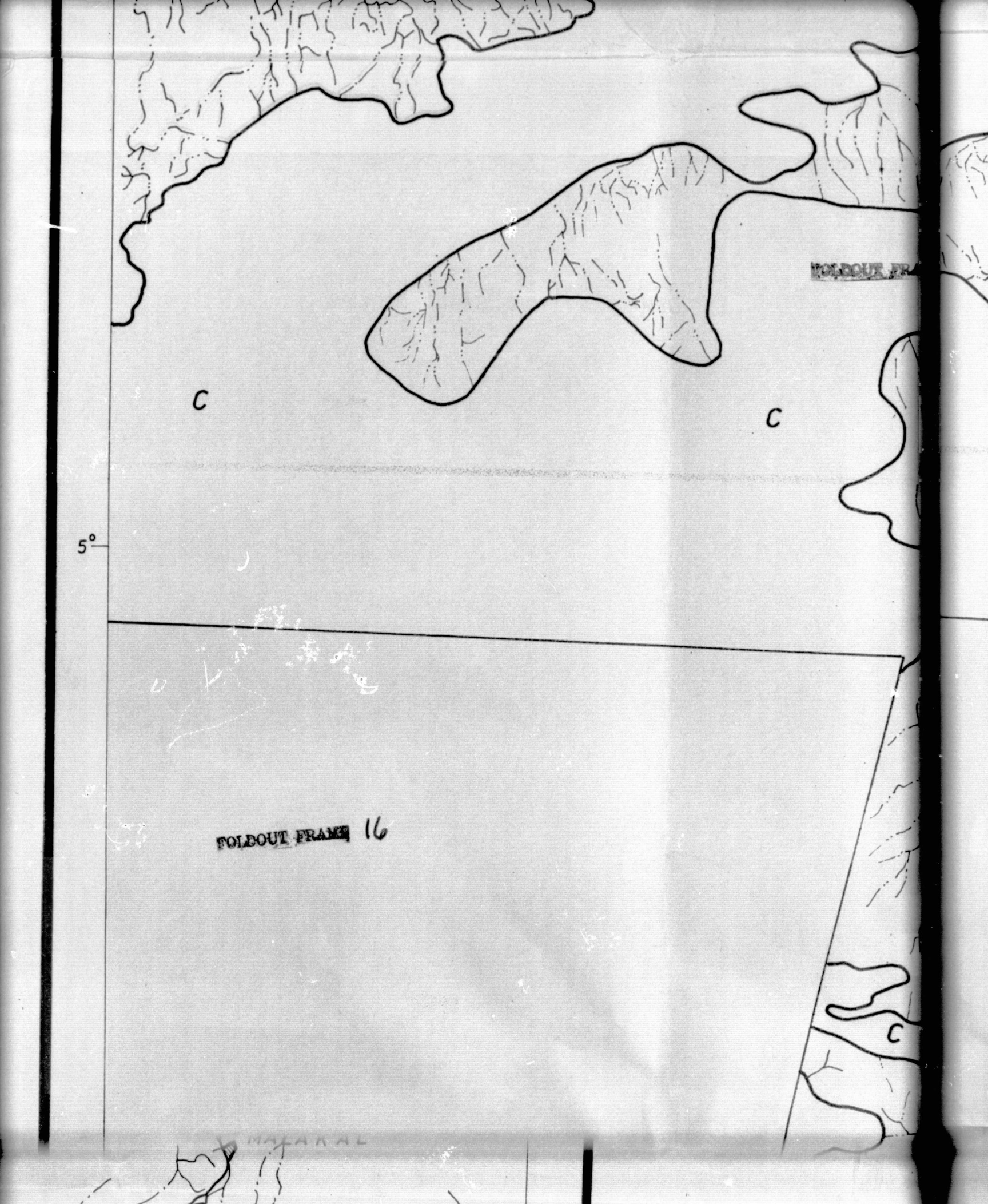


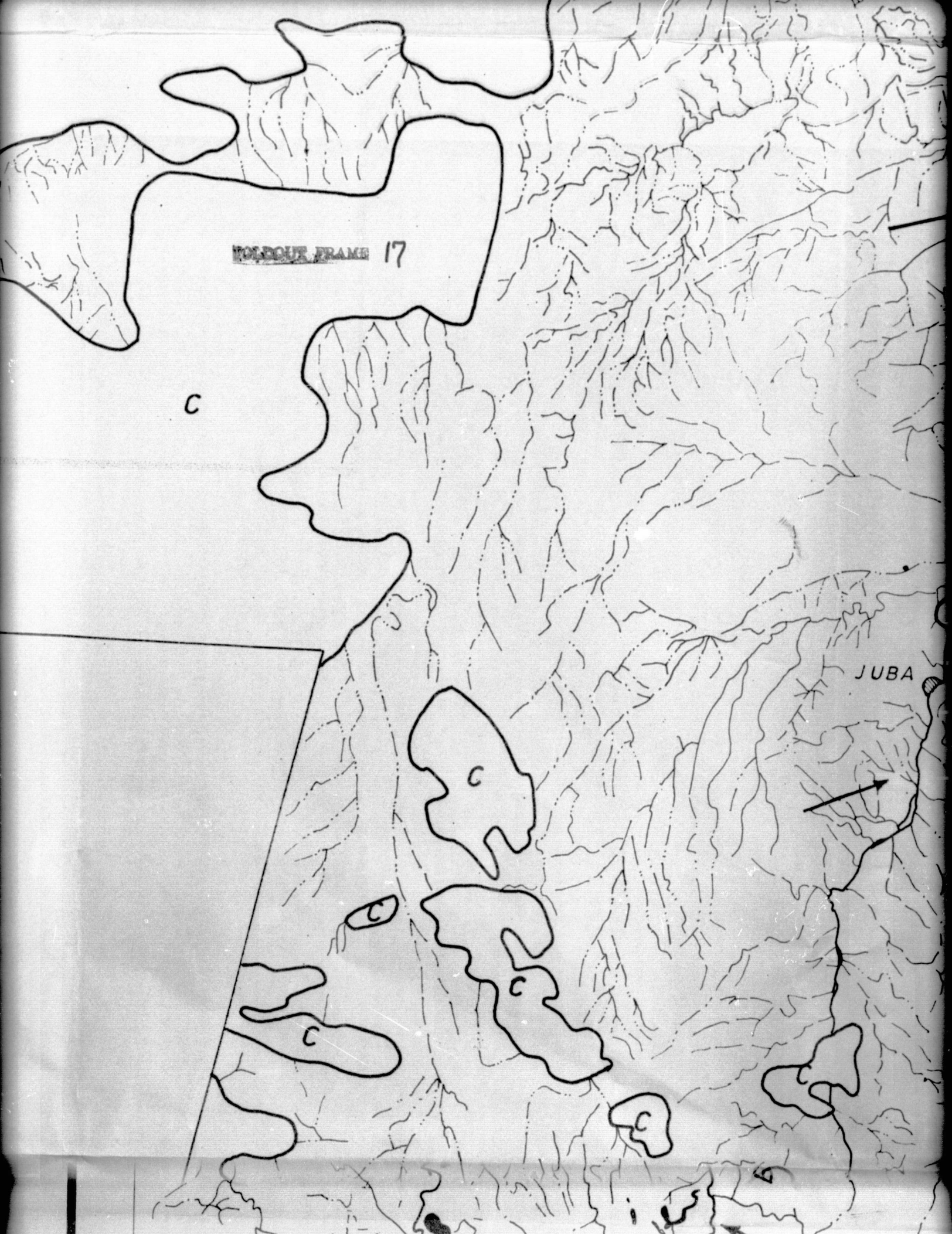
FAINT DRAINAGE LINES

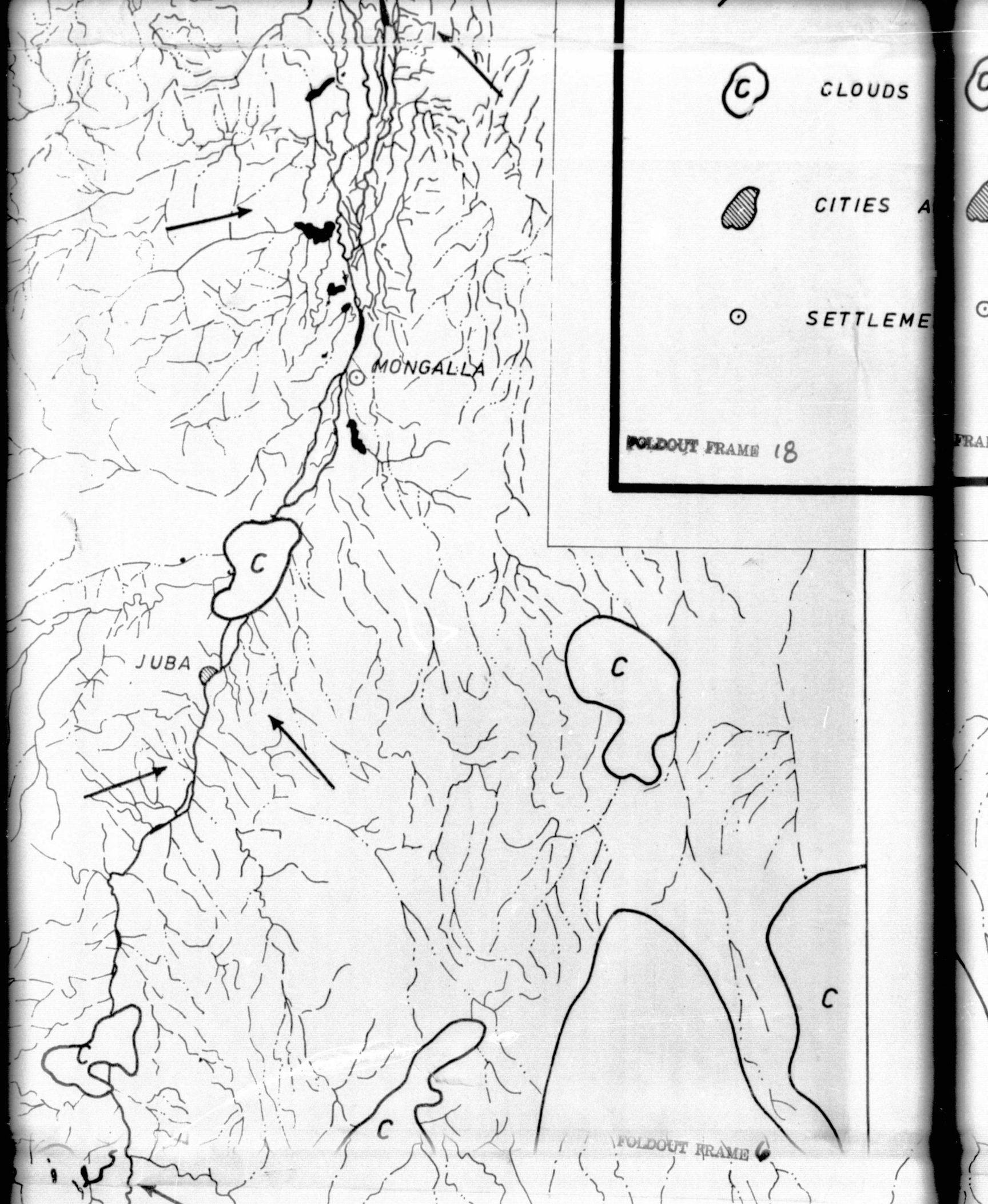


DIRECTION OF WATER FLOW




C
C
5°
FOLDOUT FRAME 16
C


COLOUR FRAME 17
C
C
C
C
C
JUBA

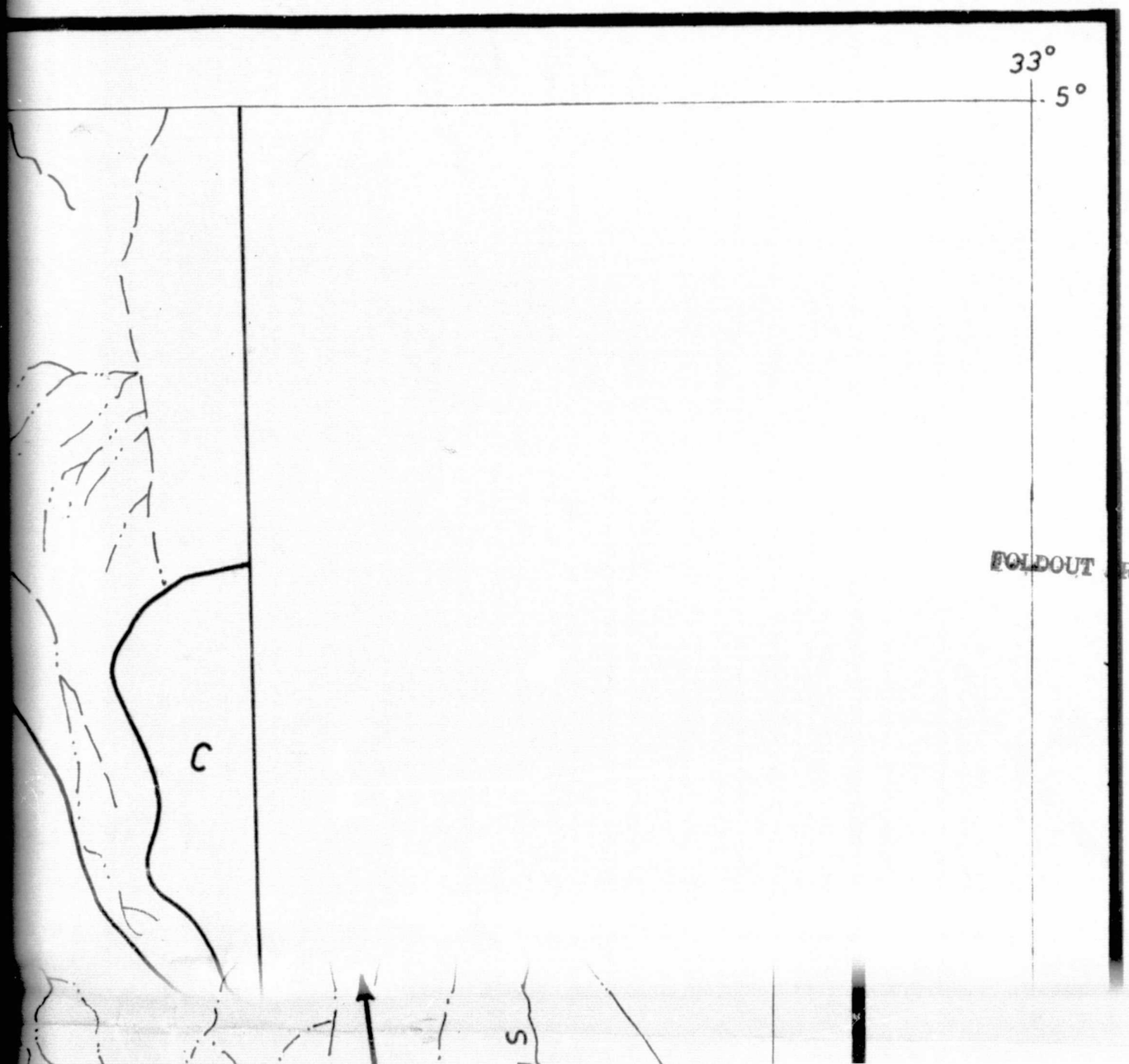

C
CLOUDS
CITIES A
SETTLEME
MONGALLA
JUBA
C
C
C
C
FOLDOUT FRAME 18
FOLDOUT FRAME 6

C CLOUDS

CITIES AND TOWNS

⊙ SETTLEMENTS AND SMALL TOWNS

FRAME 18



FOLDOUT FRAME 19

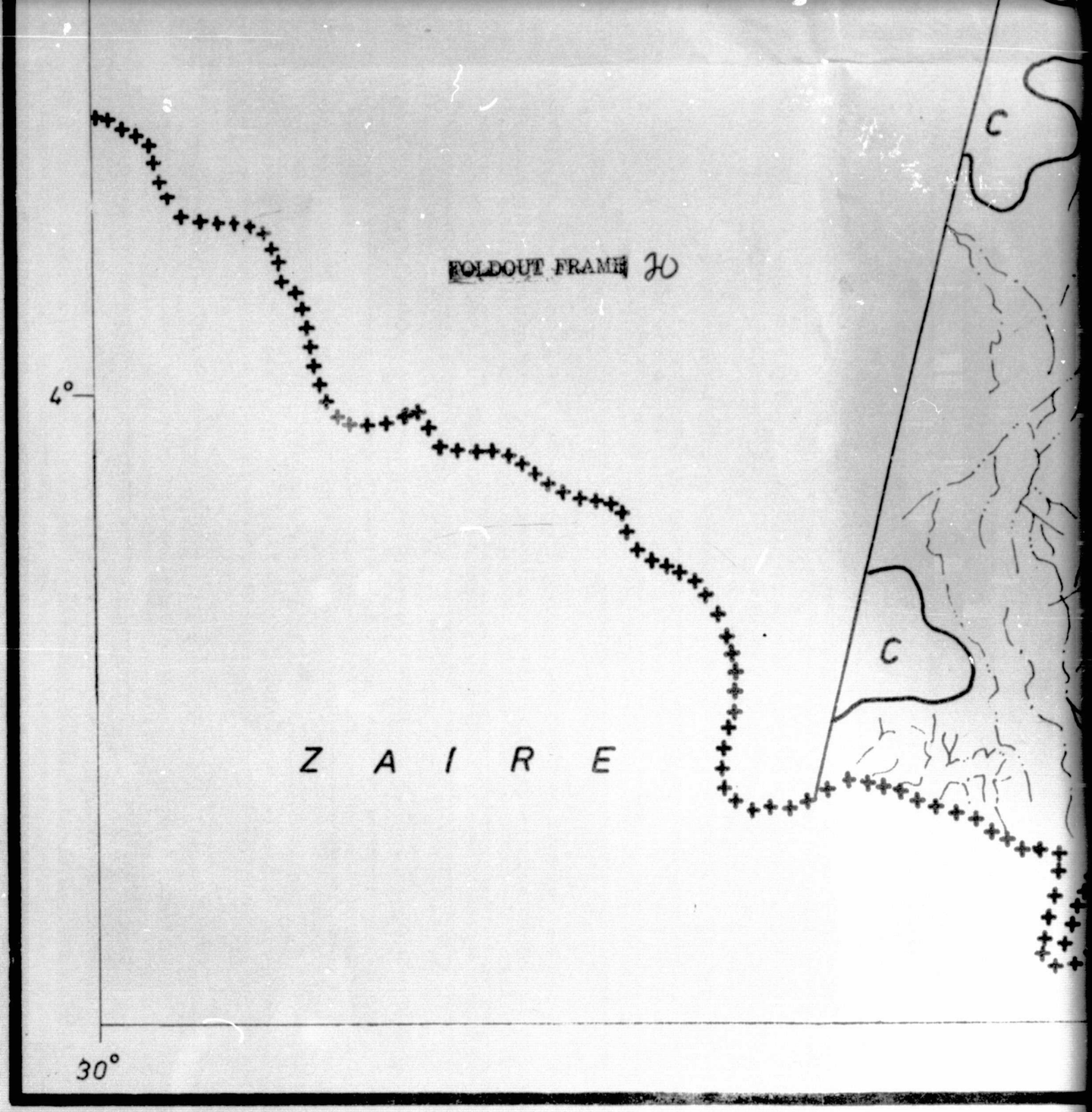
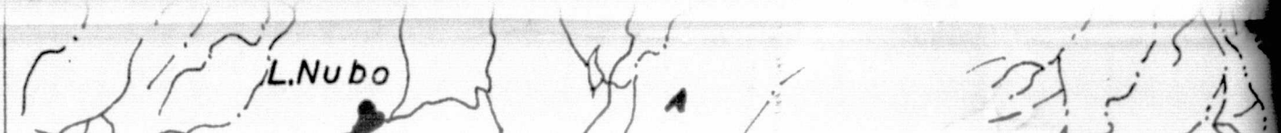
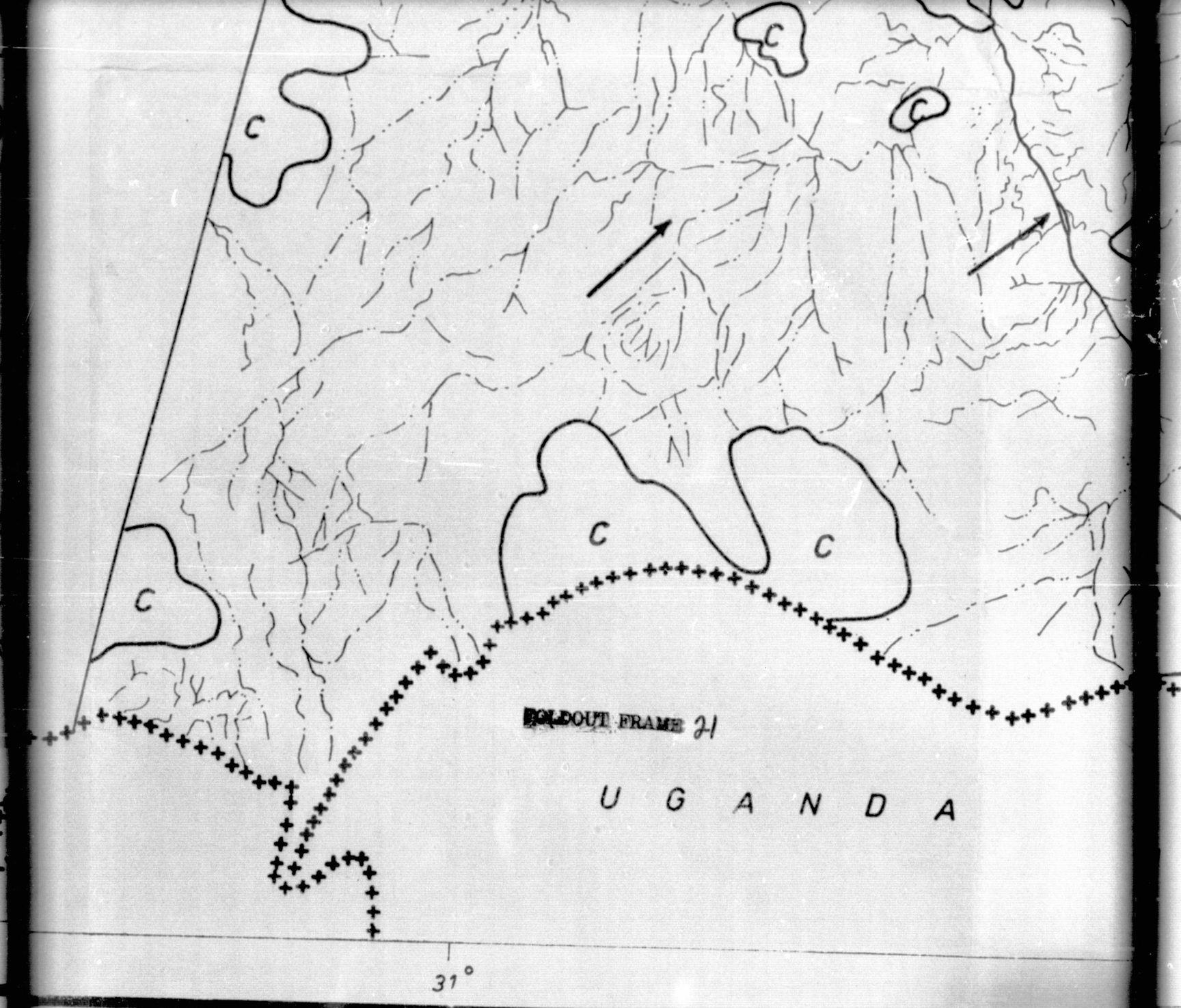


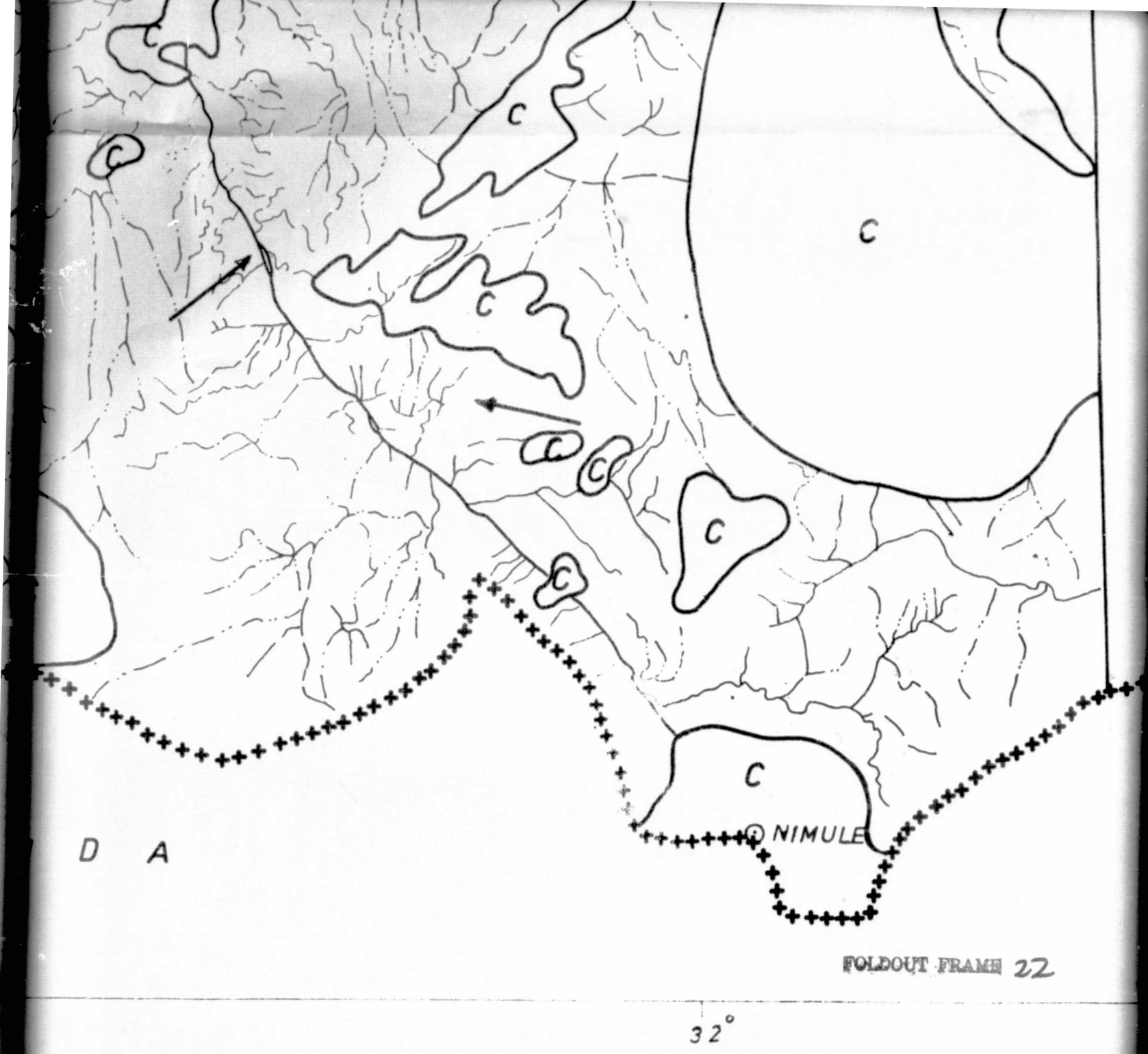
FIG. 2b. DRAINAGE





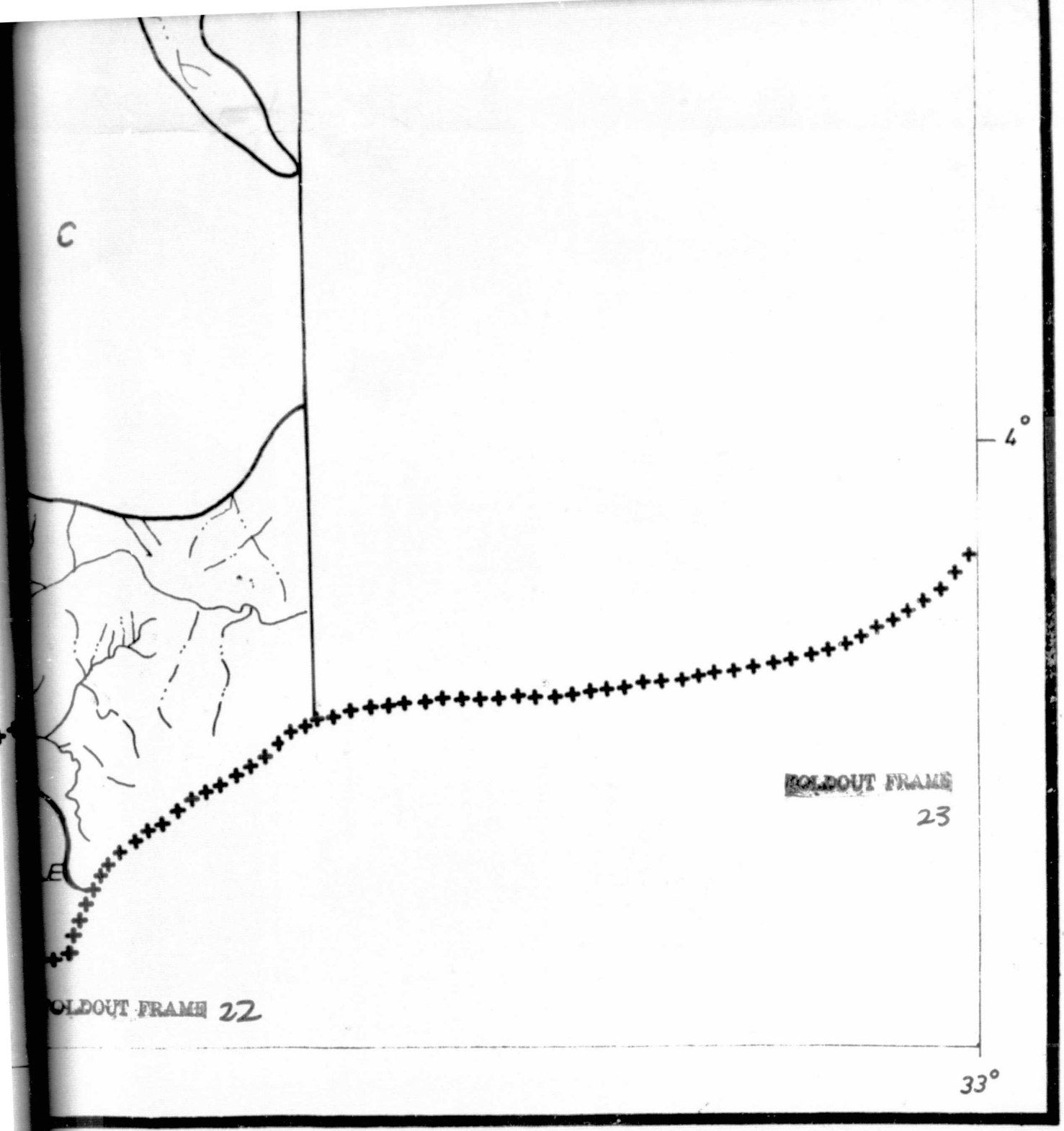
DRAINAGE MAP OF THE JONGLEI CANA

(FROM LANDSAT SATELLITE



NGLEI CANAL PROJECT AREA, SOUTHE

SATELLITE IMAGES, OCT. & NOV. 1973).



, SOUTHERN SUDAN

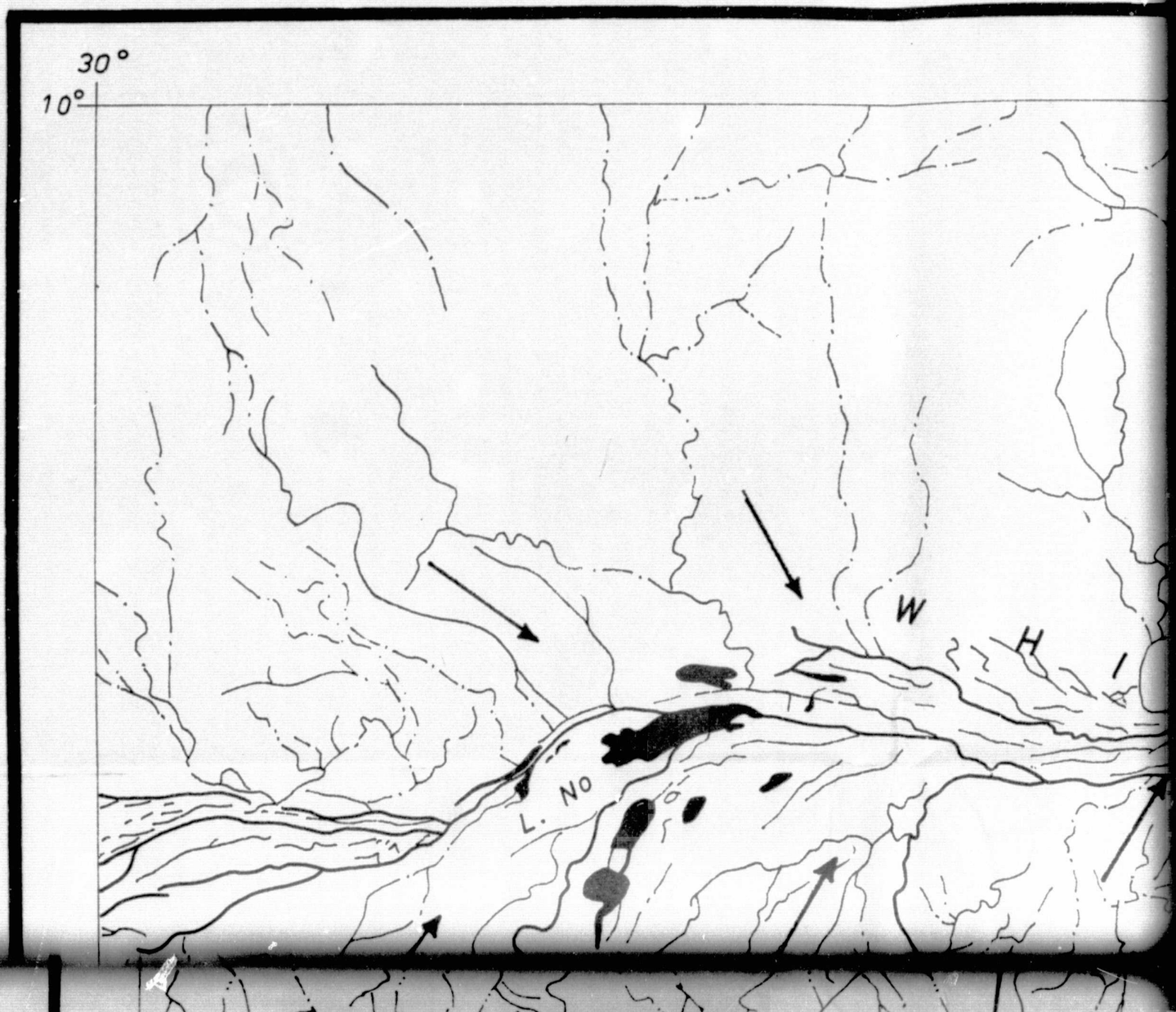
1973).

AVAILABLE FRAME

REMOTE SENSING CENTER

ACADEMY OF SCIENTIFIC RESEARCH AND TECH

CAIRO - EGYPT

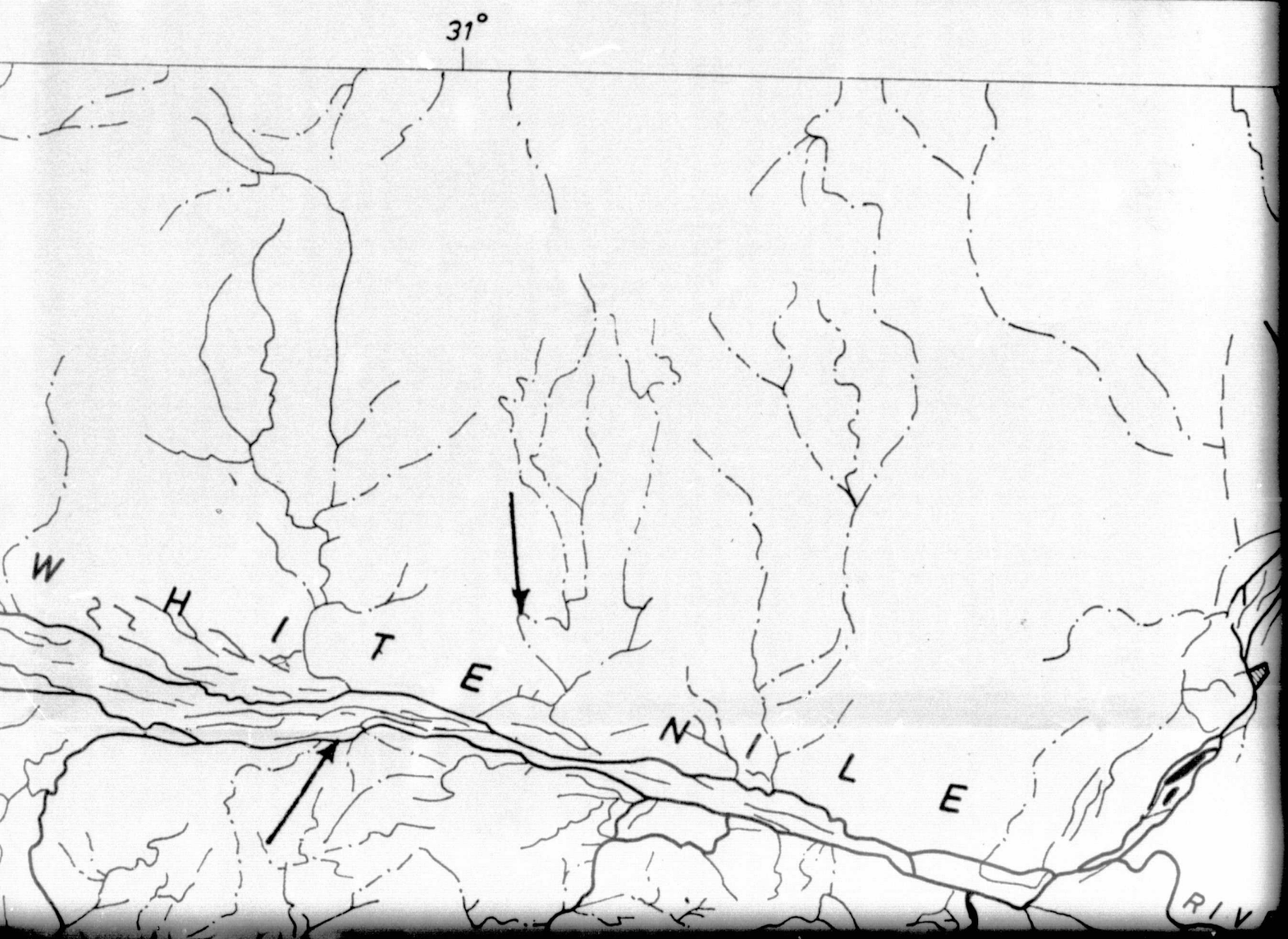


FOLDOUT FRAME 2

CENTER

CH AND TECHNOLOGY

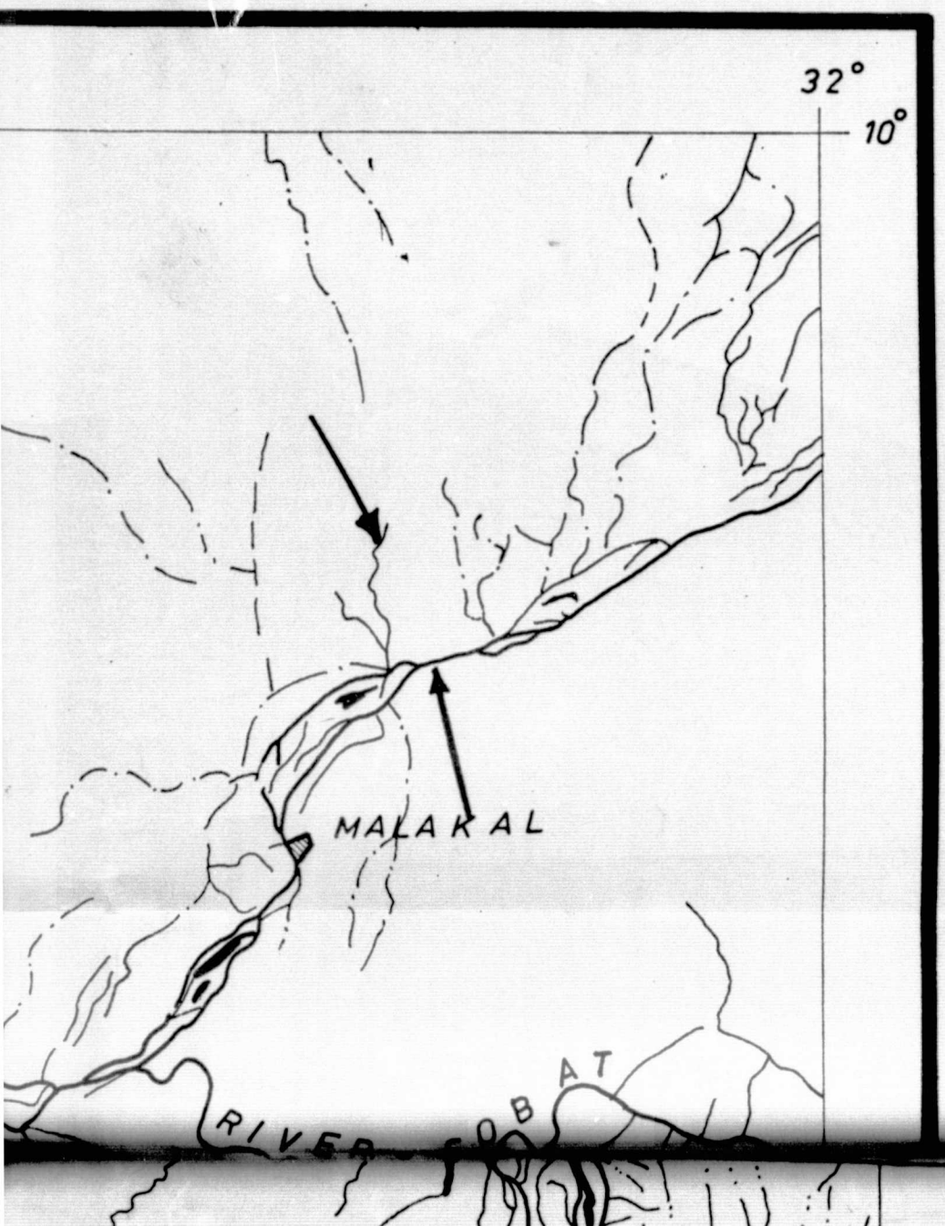
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FOLDOUT FRAME 3

MINISTRY OF IRRIGATION
ARAB REPUBLIC OF EGYPT

THE PERM
COMMIS



MINISTRY OF IRRIGATION,
ARAB REPUBLIC OF EGYPT

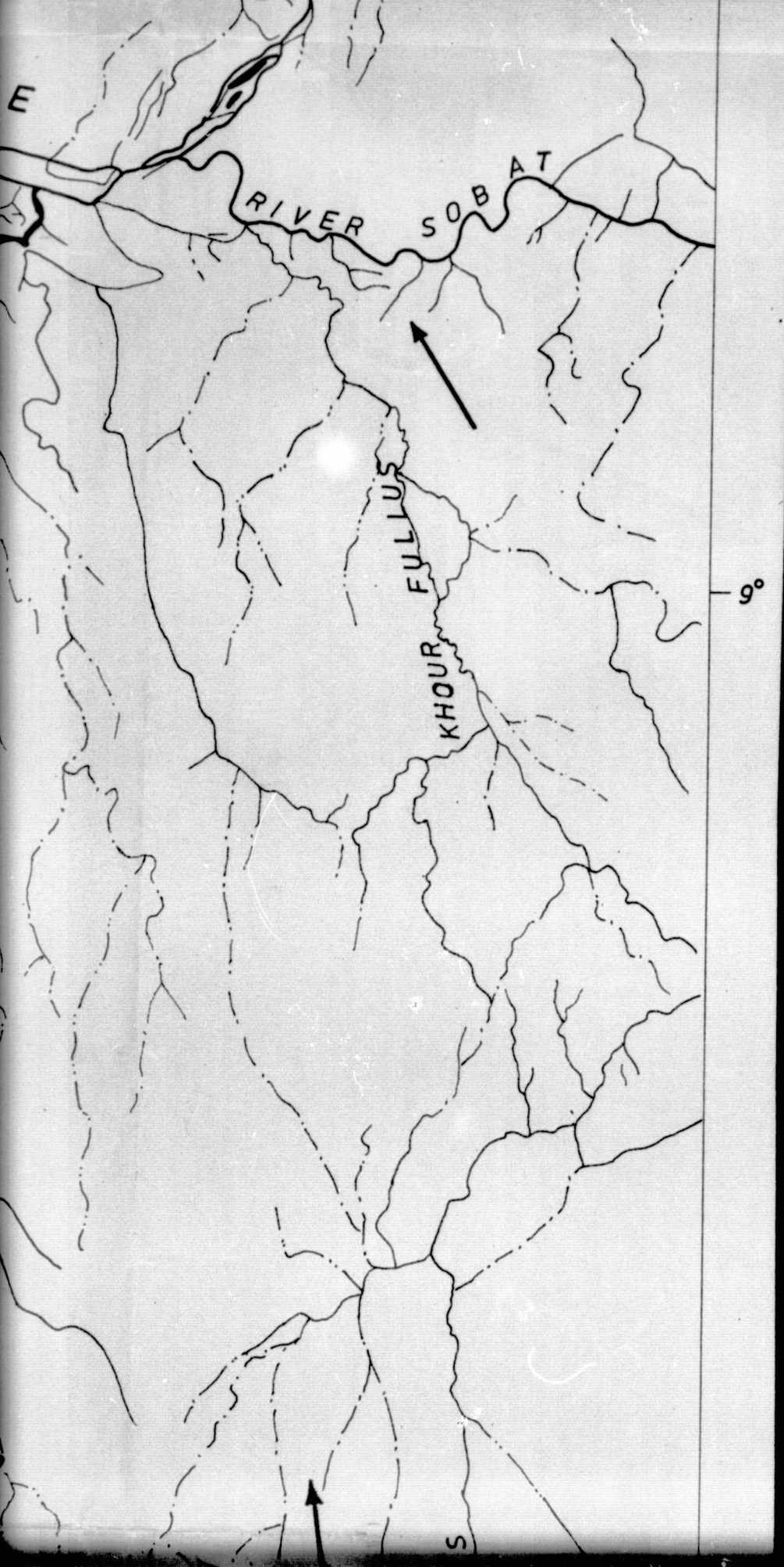
MINISTRY OF IRRIGATION,
SUDAN DEMOCRATIC REPUBLIC

THE PERMANENT JOINT TECHNICAL
COMMISSION FOR NILE WATERS

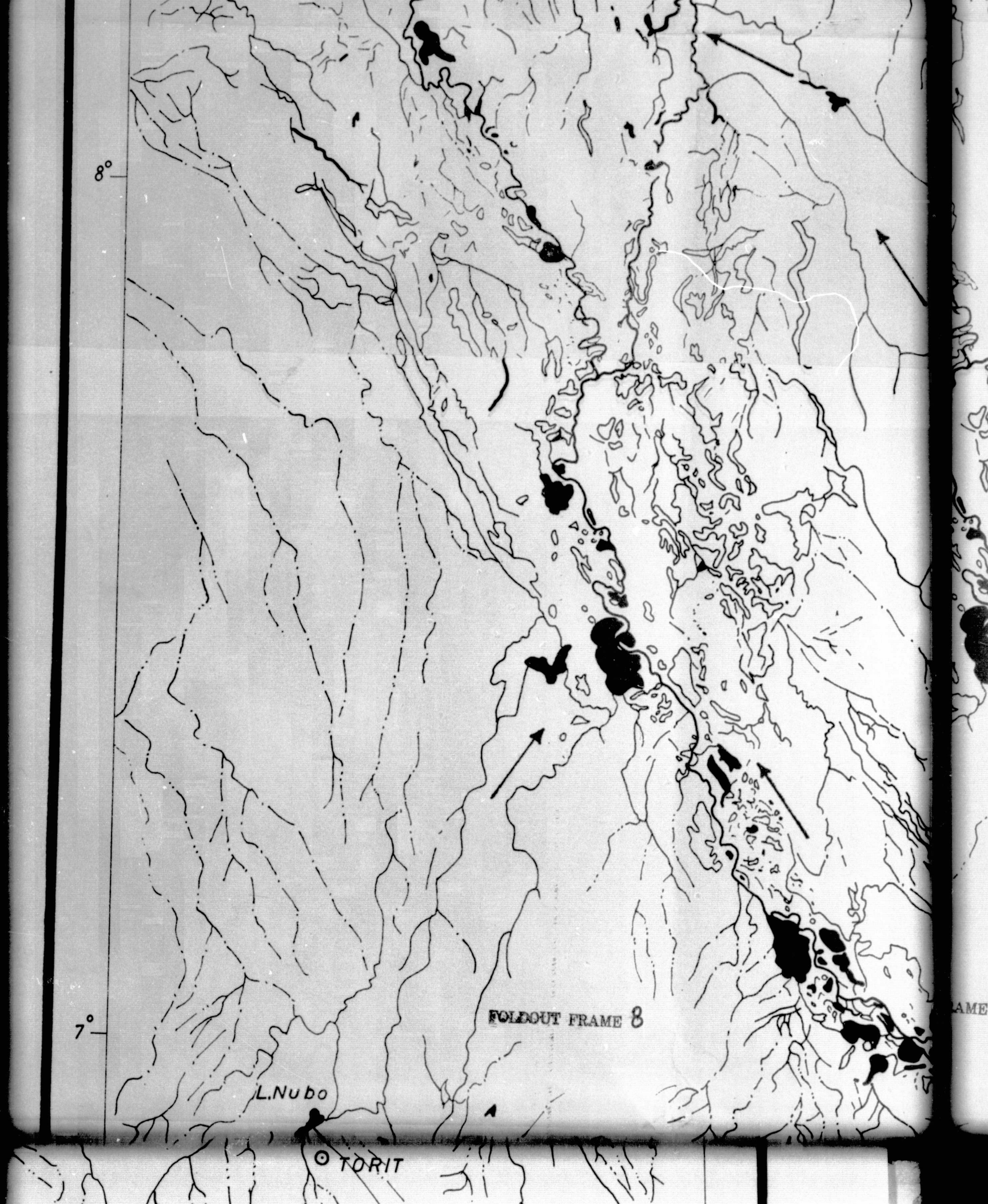
FOLDOUT FRAME 4

Fig. 9 — Swamps in the Bahr el Jebel region


E
N I L E
R I
E
BAHR EZ ZERAF
FOLDOUT FRAME 6



FOLDOUT FRAME 7


8°
7°
L.Nubo
TORIT
FOLDOUT FRAME 8


DUK F
ORIGINAL PAGE IS
OF POOR QUALITY
FOLDOUT FRAME 9
KONGOR
AME 8

KHOUR FULLUS

8°

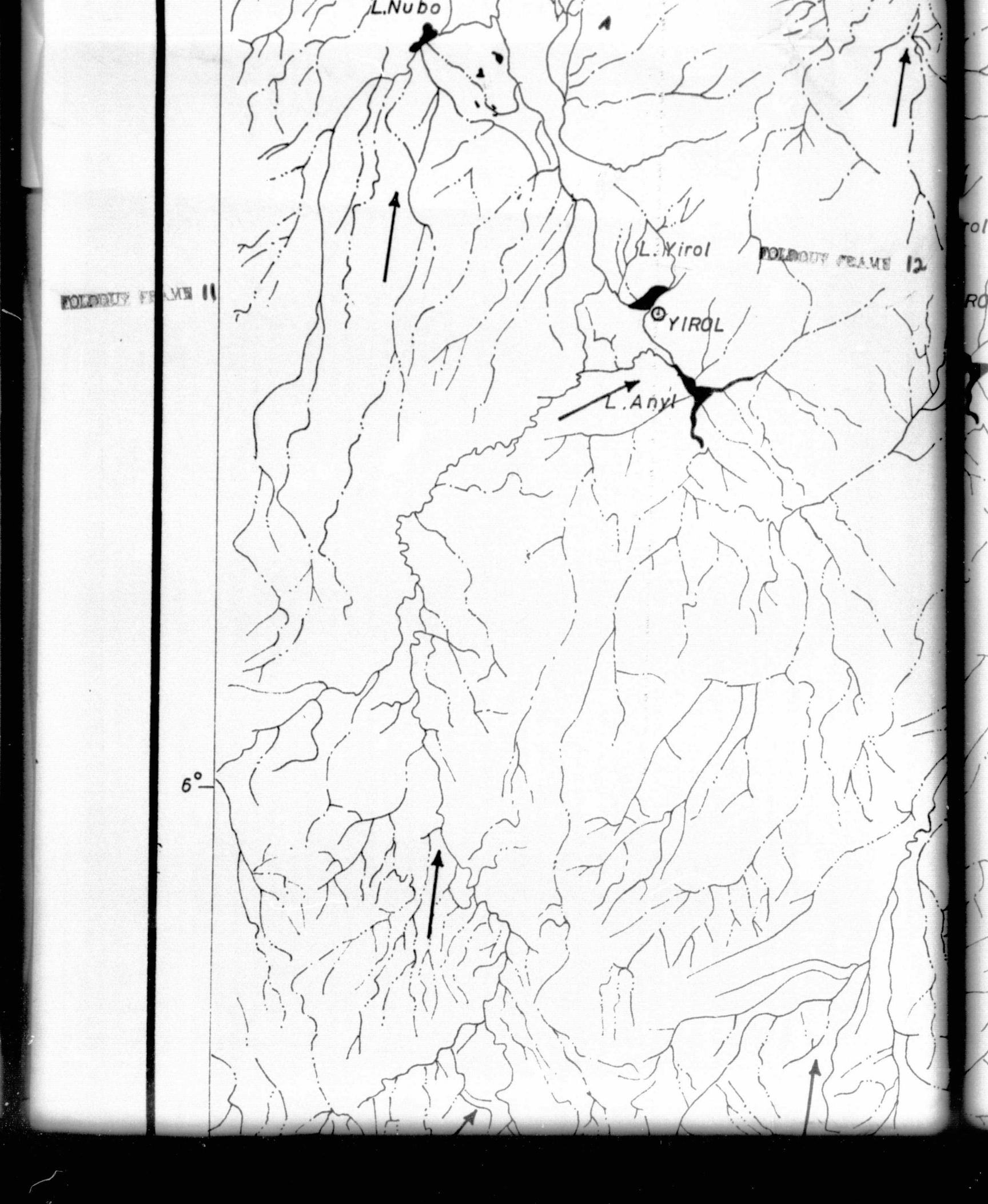
DUK FAIWIL

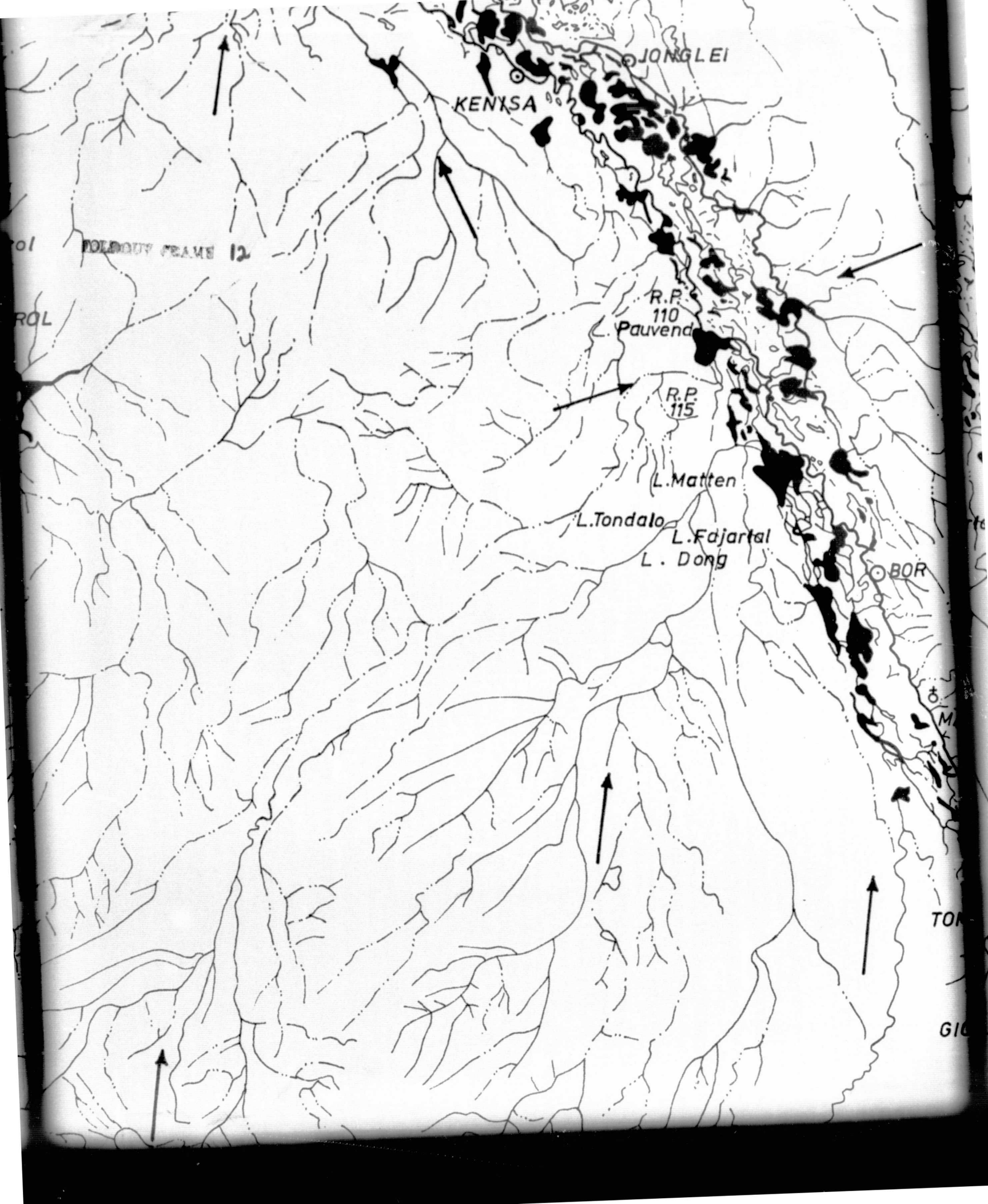
VG OR

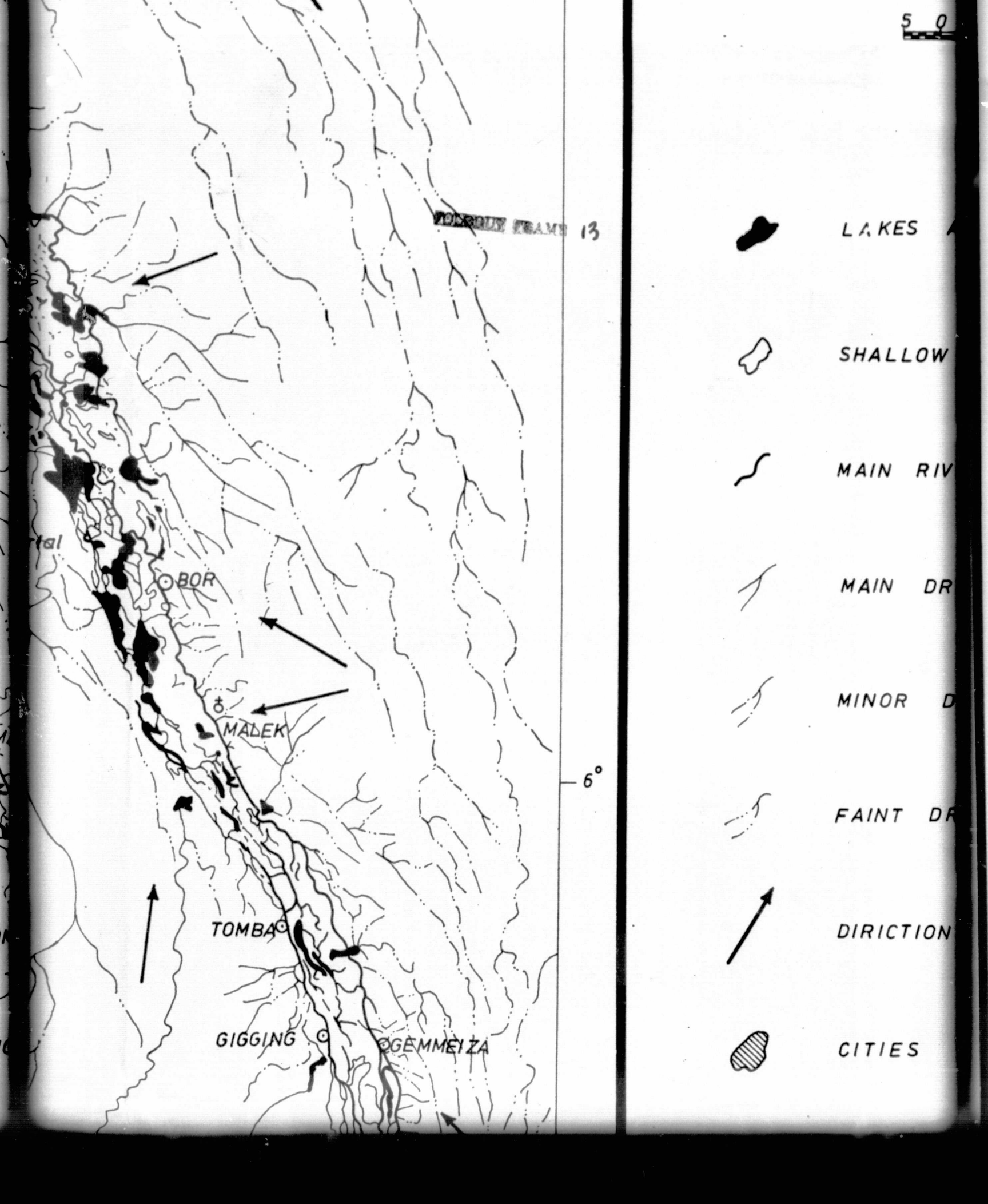
7°

5 0 5

BOLDOUT FRAME 10


L.Nubo
L. Kirol
YIROL
L. Anyi
FOLDOUT FRAME 12
FOLDOUT FRAME 11
6°


JONGLEI
KENYSA
FOLDOUT FRAME 12
R.P.
110
L. Pauvend
R.P.
115
L.Matten
L.Tondalo
L.Fajartal
L. Dong
BOR


5 0
LAKES
SHALLOW
MAIN RIV
MAIN DR
MINOR D
FAINT DR
DIRICTION
CITIES
BOR
MALEK
TOMBA
GIGGING
GEMMEIZA
6°

5 0 5 10 15 20 25 30 35 Km

LEGEND



LAKES AND WATER PONDS



SHALLOW WATER BODIES

FOLDOUT FRAME 14



MAIN RIVER CHANNELS



MAIN DRAINAGE LINES



MINOR DRAINAGE LINES



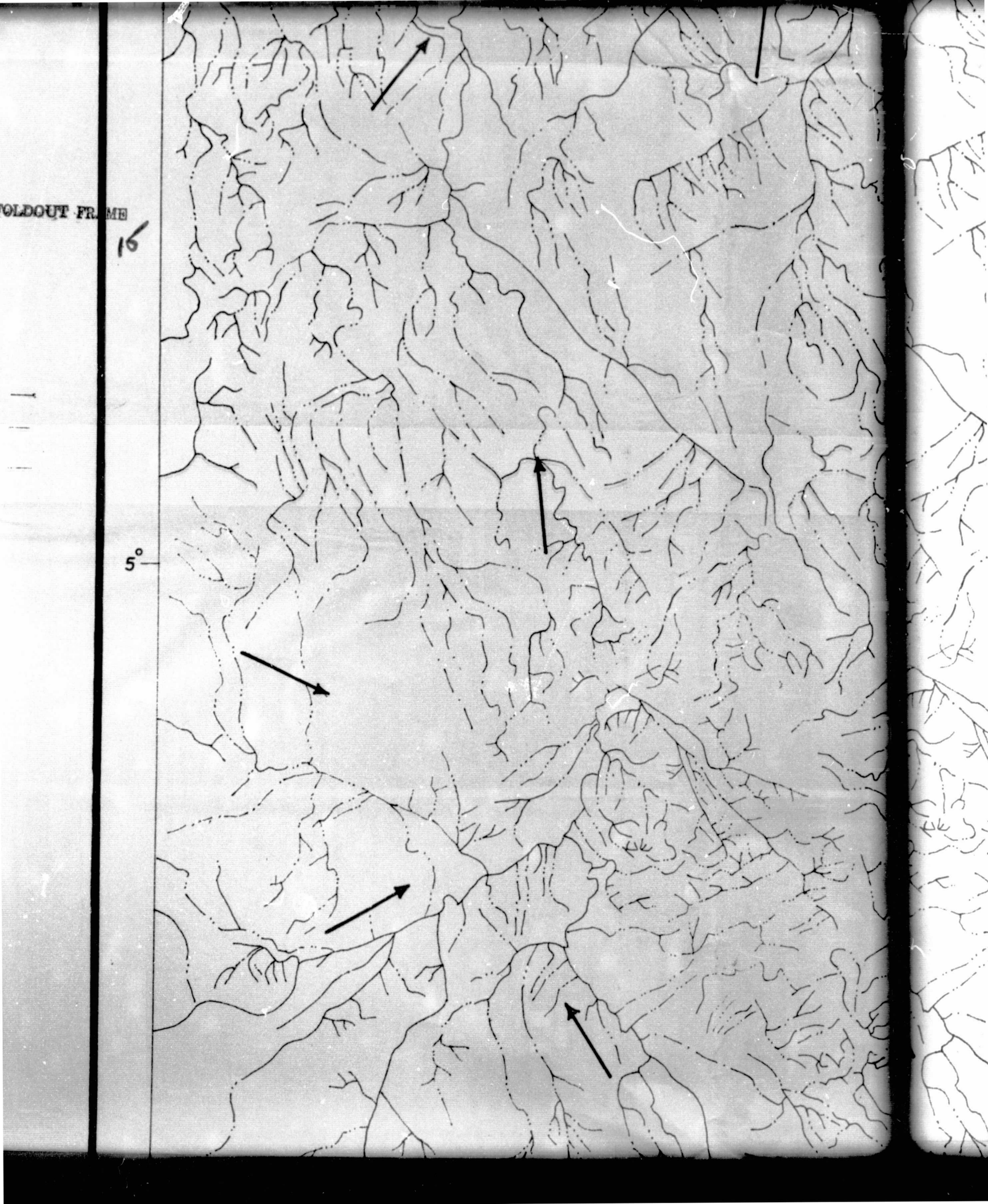
FAINT DRAINAGE LINES



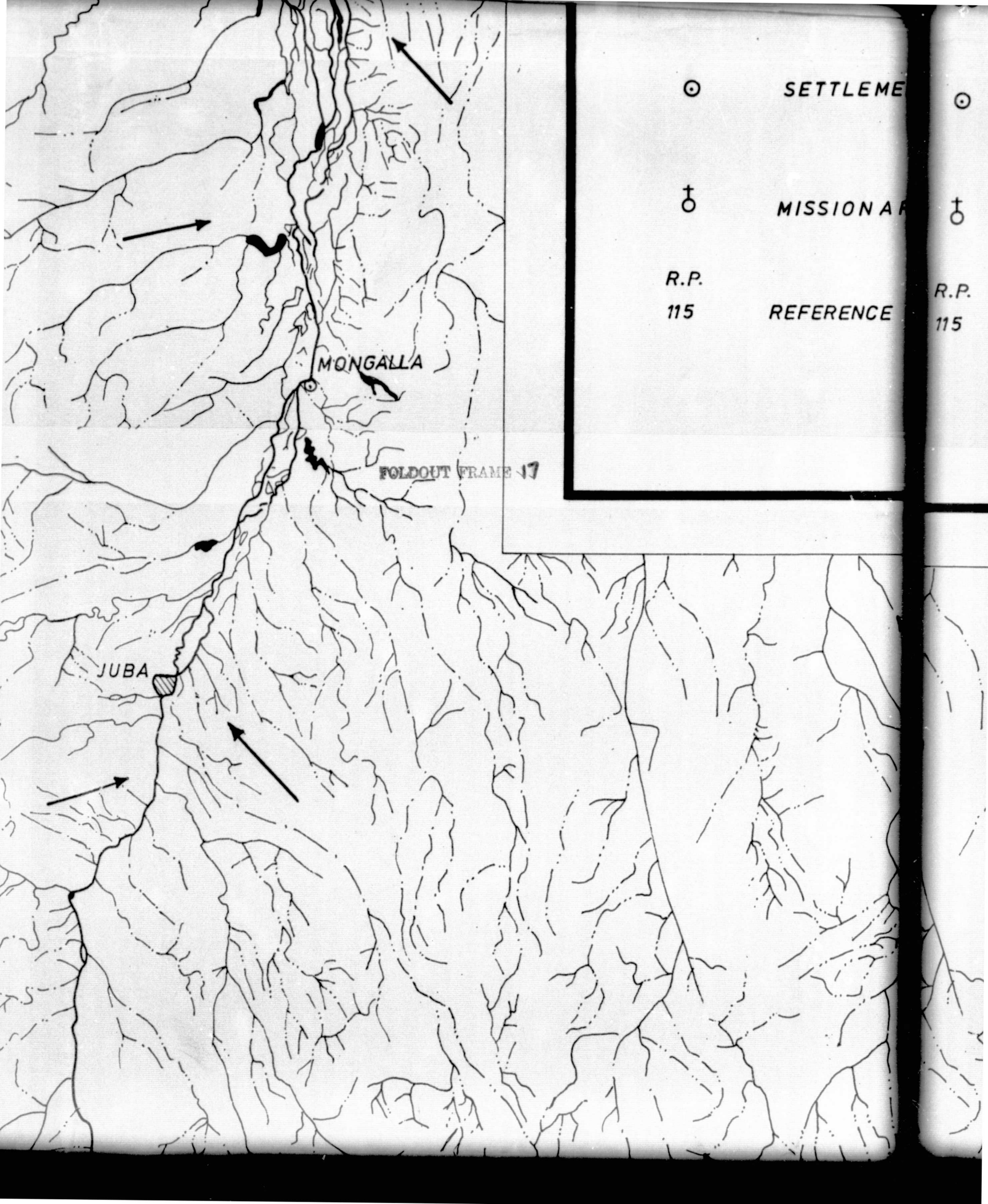
DIRICTION OF WATER FLOW



CITIES AND TOWNS


OLDOUT FR ME
16
5°


BOLDQUE FRANCE 16
JUBA

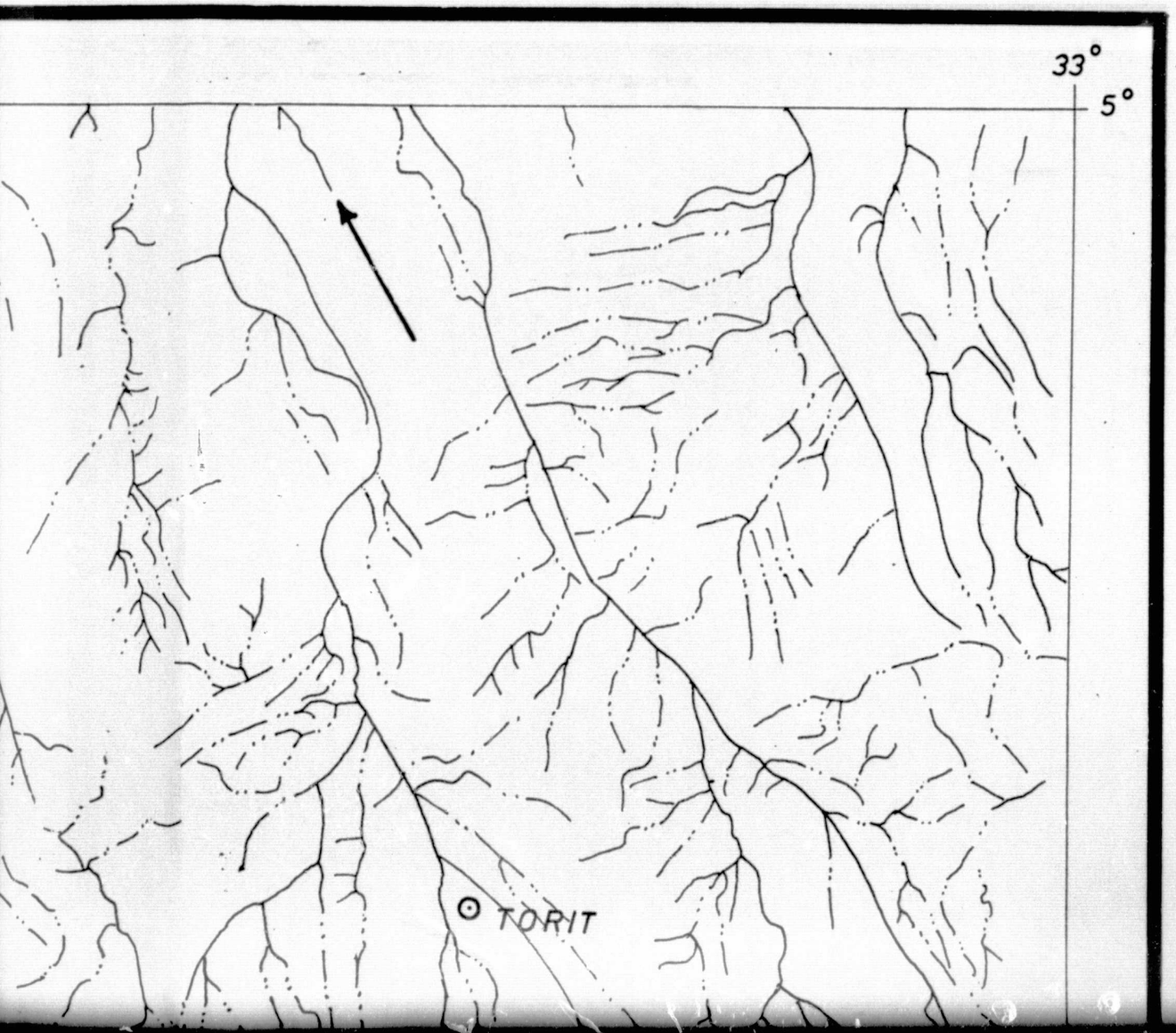

SETTLEME
MISSION A
R.P.
115
REFERENCE
MONGALLA
JUBA
FOLDOUT FRAME 17

⊙ SETTLEMENTS AND SMALL TOWNS

† MISSIONARIES

.P.
5 REFERENCE PIONT

FOLDOUT FRAME 18



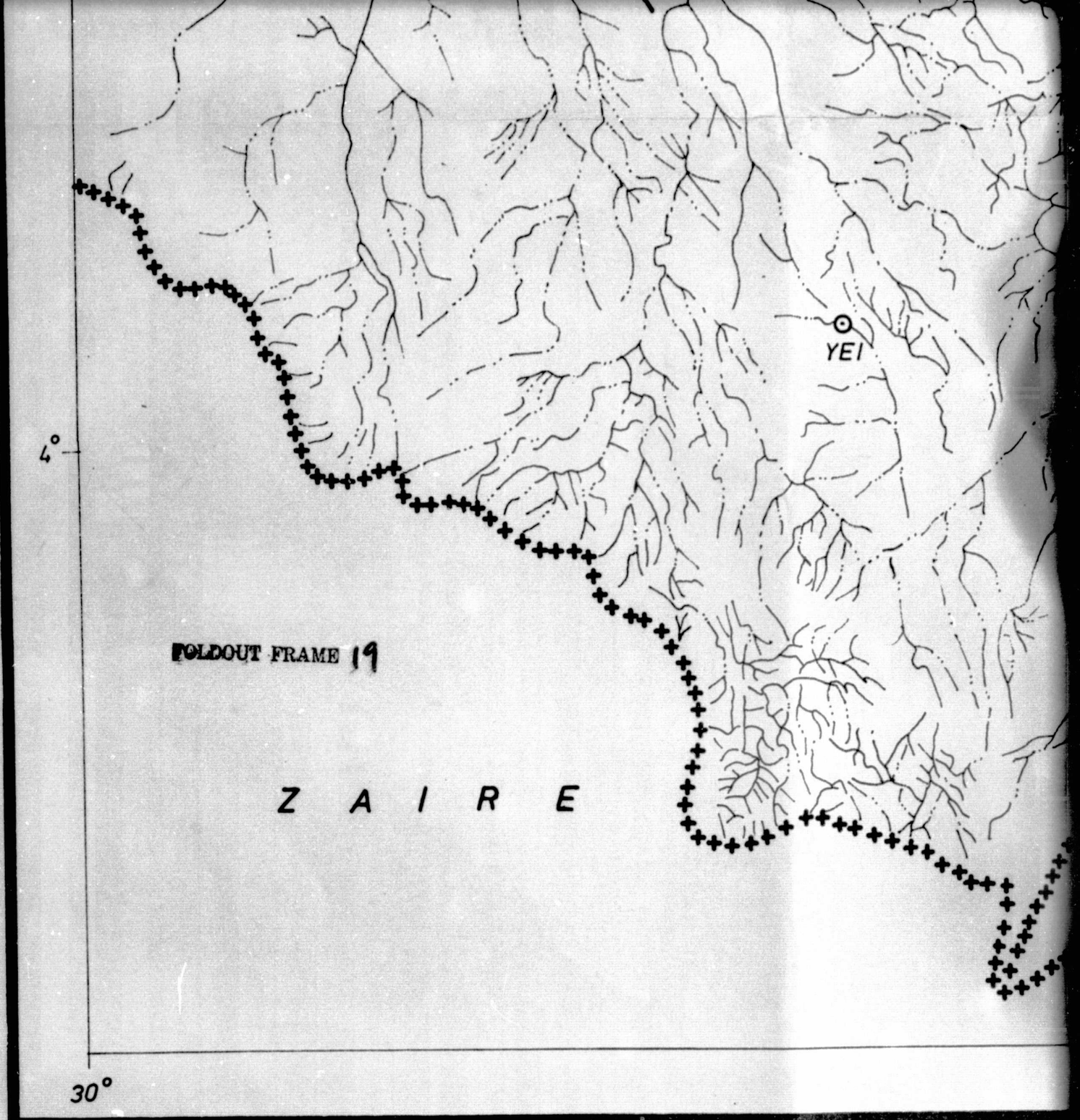
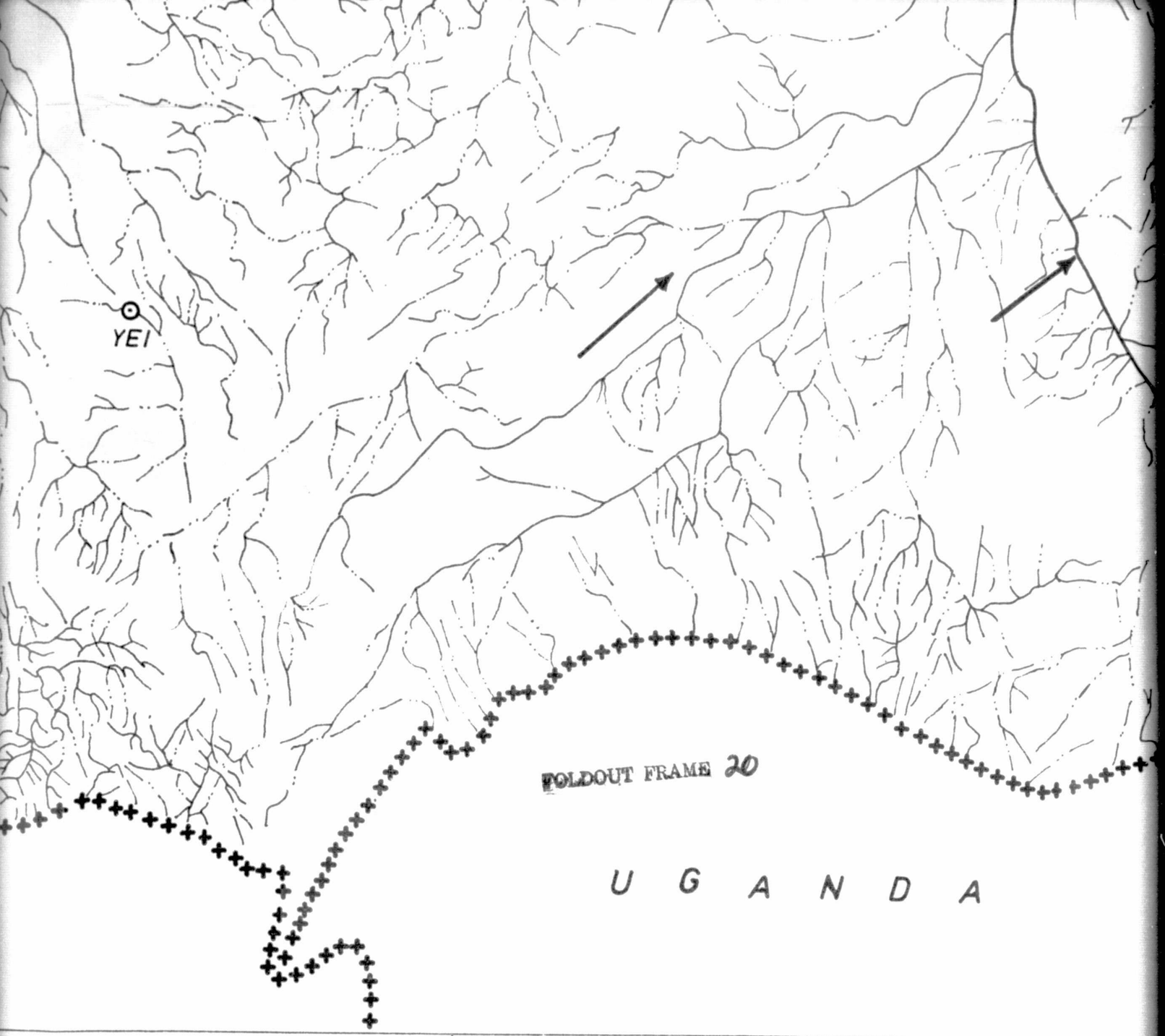


FIG. 2ª DRAINAGE

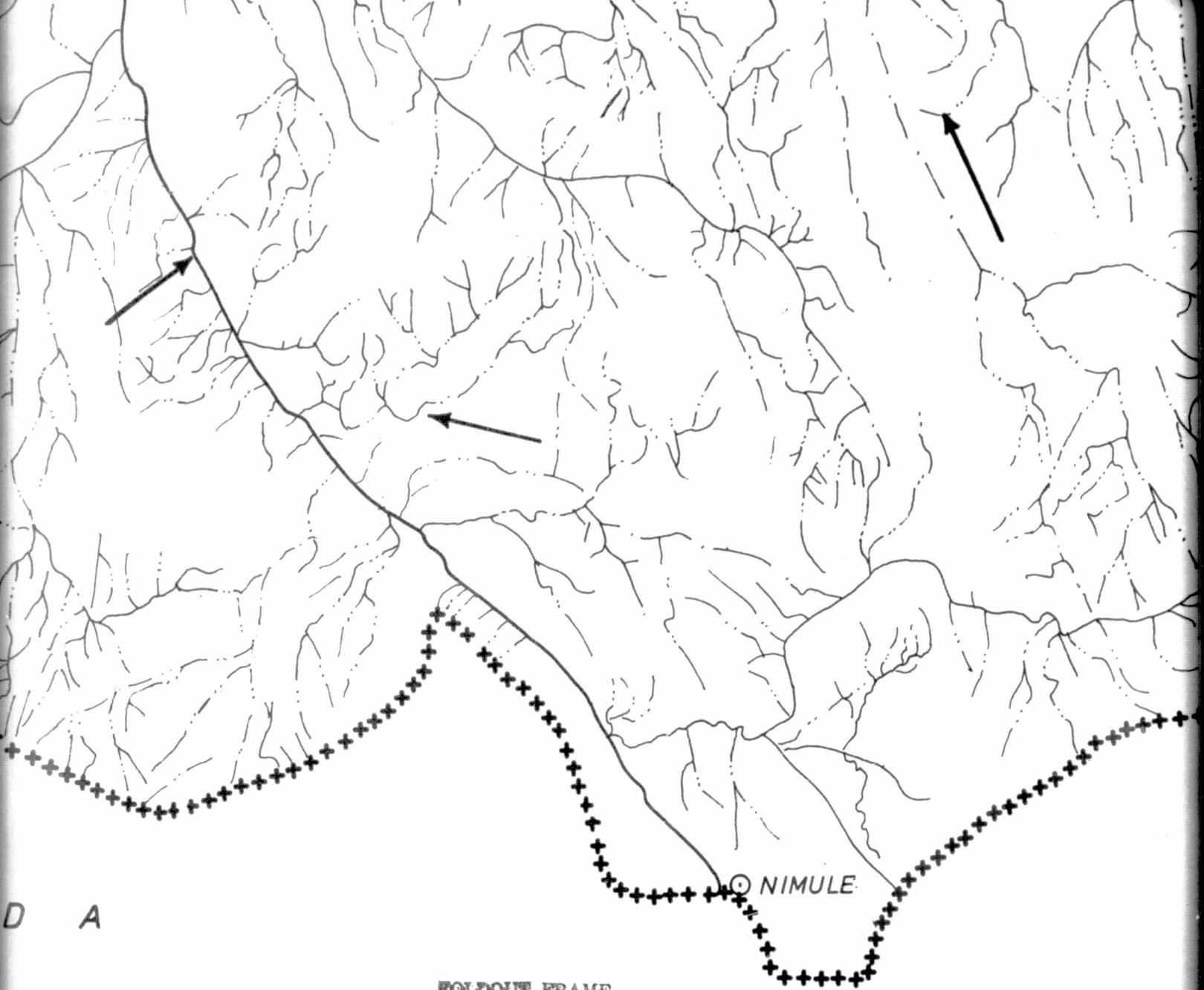
DR

1



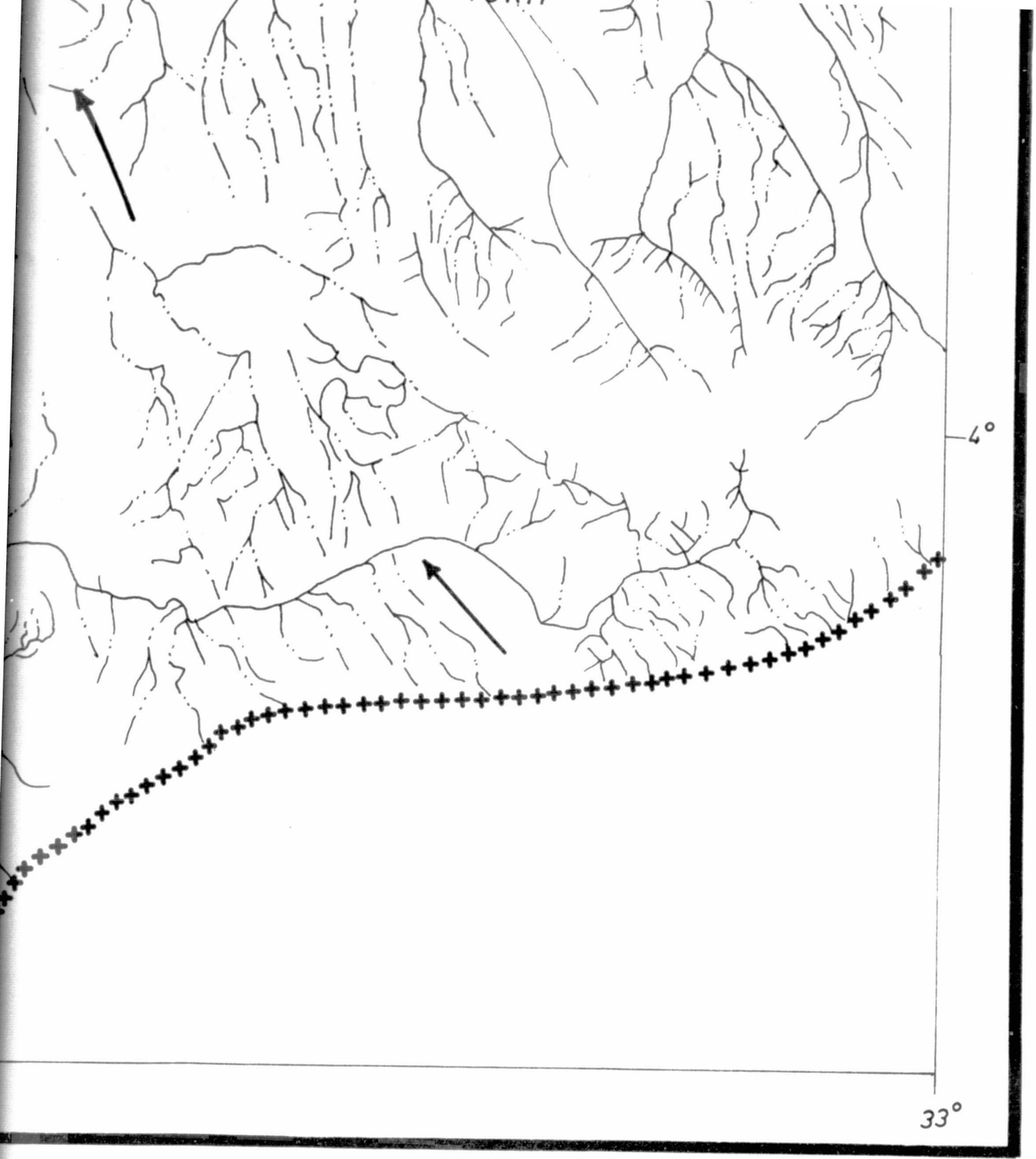
DRAINAGE MAP OF THE JONGLEI CANAL

(FROM LANDSAT SATELLITE



GLEI CANAL PROJECT AREA, SOUTHERN

SATELLITE IMAGES, FEB. 1973)



SOUTHERN SUDAN

1

FOLDOUT FRAME 22